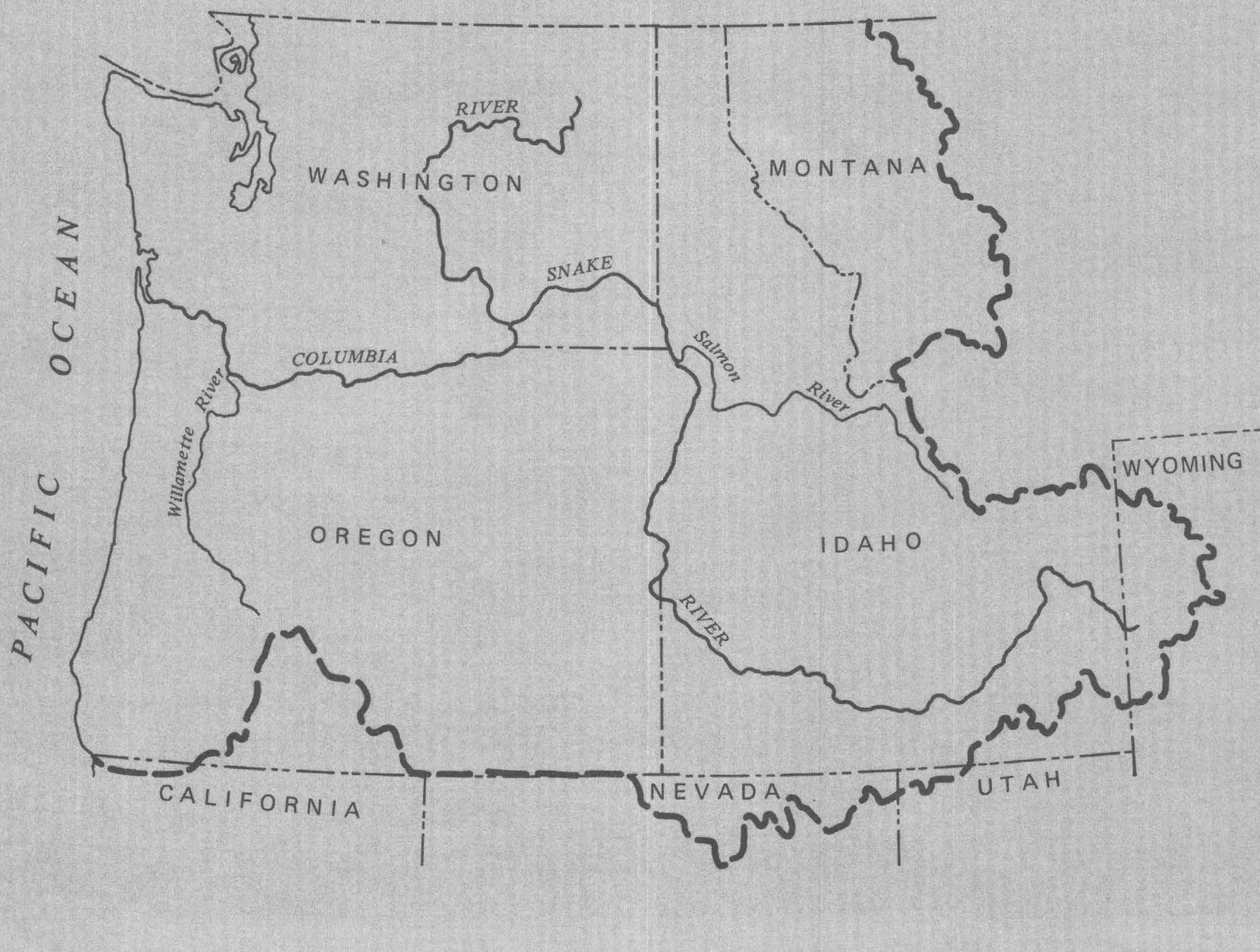
Summary Appraisals of the Nation's Ground-Water Resources— Pacific Northwest Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-S



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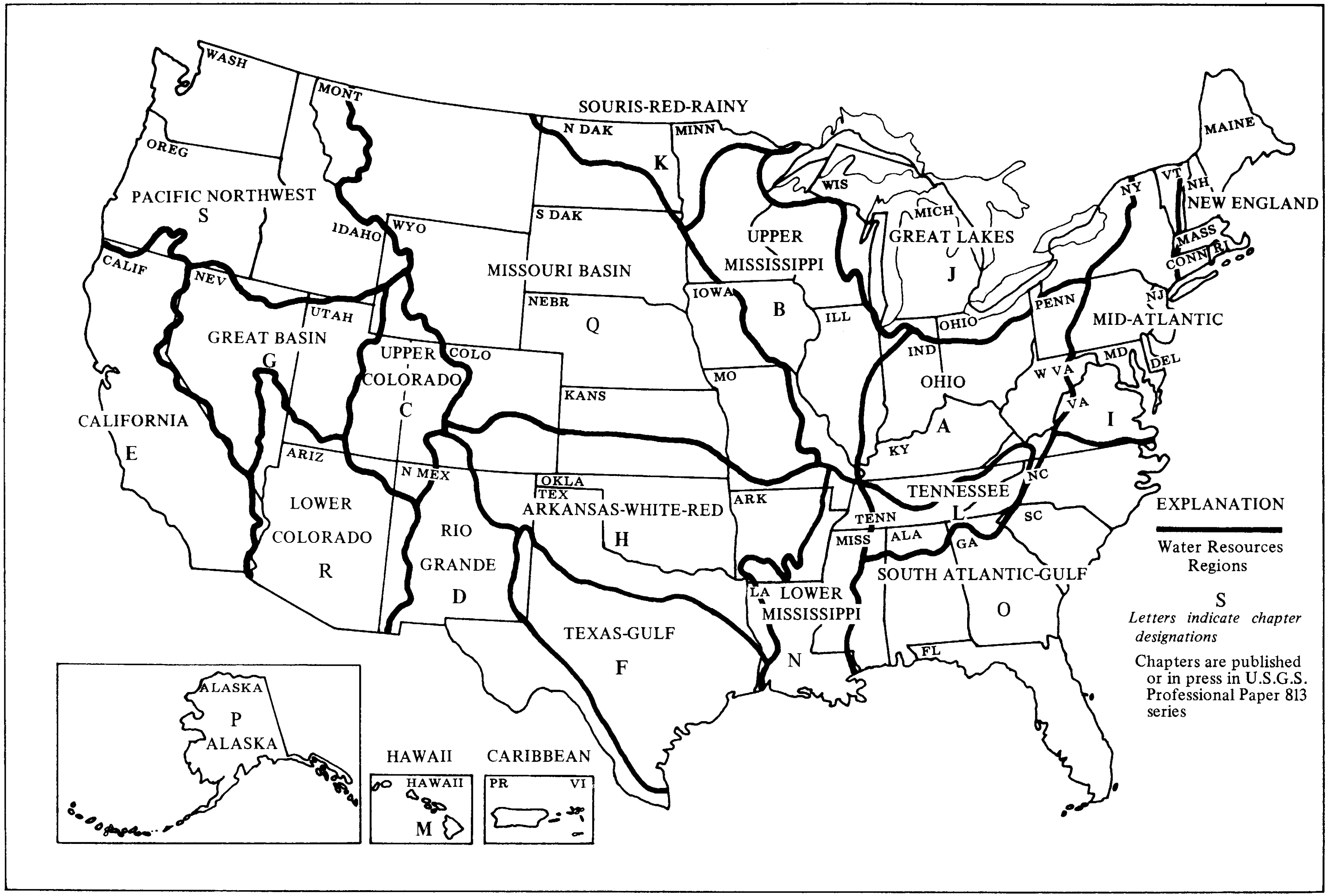

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Summary Appraisals of the Nation's Ground-Water Resources— Pacific Northwest Region

By BRUCE L. FOXWORTHY

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Opportunities and problems presented by the region's ground-water resource

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From Unit	*Abbreviation*	*Multiply by*	*To obtain Unit*	*Abbreviation*
acre		4,047	square meter	m^2
		0.4047	hectare	
cubic foot	ft^3	.02832	cubic meter	m^3
cubic feet per second	ft^3/s	28.32	liter per second	L/s
		.02832	cubic meters per second	m^3/s
cubic mile	mi^3	4.166	cubic kilometer	km^3
foot	ft	.3048	meter	m
gallon	gal	.003785	cubic meter	m^3
		3.785	liter	L
gallons per minute	gal/min	.06309	liters per second	L/s
inch	in	2.540	centimeter	cm
mile	mi	1.609	kilometer	km
million gallons per day	Mgal/d	.003785	cubic meters per day	m^3/d
square mile	mi^2	2.59	square kilometer	km^2
ton, short (2,000 pound)		.9072	ton, metric	t
		907.1848	kilograms	kg

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES—PACIFIC NORTHWEST REGION

By BRUCE L. FOXWORTHY

ABSTRACT

The Pacific Northwest Region's ground-water reservoirs are capable of providing large additional fresh-water supplies; these reservoirs become more important as undeveloped surface-storage sites and unapportioned surface-water supplies dwindle. Withdrawals of fresh water from all surface and underground sources are increasing; they may rise from the rate of 30 billion gallons per day in 1970 to about 60 billion gallons per day in 2020. By 1975 the withdrawal of ground water had increased 70 percent over the 1970 rate and accounted for 22 percent of total fresh-water withdrawal. Substantial increases in ground-water withdrawal must continue if projected water demands are to be met in the future.

Large variations exist in the availability of and needs for ground water in the region, largely because of the great variety of landforms, climate, and earth materials. More than one-half the region is underlain by rock materials capable of yielding ground water to wells at moderate to large rates; six extensive areas are identified as major ground-water reservoirs. The most significant current problems pertaining to one or more of these ground-water reservoirs are: (1) Progressively declining water levels; (2) water-quality problems; (3) waterlogging; (4) inadequate information; and (5) competition for available supplies. In the future these same problems are expected to persist and generally worsen (especially water-quality deterioration) in most of the major reservoir areas.

Management opportunities in the region include: (1) Development of new supplies and additional uses of ground water; (2) protection and enhancement of water quality; (3) reduction of waterlogging; (4) energy development from some ground-water reservoirs; (5) improving access to the ground water; (6) increased use of underground space for storage and disposal; and (7) greater use of advanced management and conservation techniques. Conjunctive use of surface and ground water to provide greater available supplies probably is the most promising water-management opportunity. However, if the full potential of the ground-water resources is to be realized, important constraints, including present water-right structures and serious deficiencies in information, must be overcome.

INTRODUCTION

The Pacific Northwest, a region largely drained by The Columbia River, the second biggest river in the Nation, has the reputation for having abundant water. The long-term average discharge of stream water from the region has been estimated at 384,000 cubic feet per second—much greater than from most other U.S. regions of comparable area (Columbia-North Pacific Technical Staff, 1970b, p. 18). In spite of the apparent large total supply, however, water is not always available where and when it is needed. The distribution of runoff throughout the region is extremely uneven, and large variations in streamflow occur on a monthly, yearly, and long-term basis. Serious competition exists between irrigation diversions and important instream uses of surface water, and thousands of square miles of irrigated farmland are subject to water shortages. Although additional supplies of surface water can be developed at many places, problems associated with surface-water supplies are likely to worsen in the future as demands for water increase.

The Pacific Northwest Region's ground-water reservoirs, on the other hand, are capable of providing large additional fresh-water supplies, represent huge amounts of storage space for surplus runoff, and have the potential for greatly alleviating present and foreseeable water-supply problems. As undeveloped surface-storage sites and unapportioned surface-water supplies dwindle, the ground-water reservoirs of the region should become the focus of water-management schemes. Traditionally, however, the ground-water resources have been accorded a subordinate role in regional resource planning, owing partly to the major importance of surface water in the region and partly, no doubt, to a general lack of understanding of the potential value of the ground-water resource and of the underground space containing it.

The purpose of this report is to summarize the general status and significance of the region's ground-water resources, some of the likely demands upon them in the future, and major problems and constraints associated with their use, and to evaluate some of the ways in which the ground-water reservoirs can be further utilized. The intended audience includes, but is not restricted to, officials responsible for resource development and administration, and experienced in water-resource planning and management, but with somewhat limited familiarity with the ground-water resource. The report is intended to focus attention on the importance of, and opportunities for, ground-water management and conjunctive use of ground waters and surface waters to meet water needs under the changing conditions that seem likely within the next several decades.

The data on which this report is based were gleaned mainly from reports of many earlier studies. The U.S. Geological Survey has made water-resource studies in the region since about 1900, largely in cooperation with State, local, and other Federal agencies. Many of the reports of those studies are listed in the section on "Selected References," along with several reports of studies by other agencies or individuals on subjects that are especially pertinent to this report. Information derived from these earlier reports was augmented by the writer's experience on several hydrologic studies in this region and by contributions from ground-water hydrologists currently working in the individual States of the region. Contributors included E. G. Crosthwaite and A. M. La Sala, Jr., Boise, Idaho; A. R. Leonard and J. H. Robison, Portland, Oreg.; R. G. McMurtrey and J. A. Moreland, Montana; and K. L. Walters, Tacoma, Wash.

Especially helpful to the present study were two earlier reports containing water-resources data and interpretations of regional and subregional scope, compiled mostly by colleagues in the U.S. Geological Survey. Those reports are: "The role of water in shaping the economy of the Pacific Northwest" (Bodhaine and others, 1965); and the "Water Resources" appendix (app. 5) of the "Columbia-North Pacific Region comprehensive framework study of water and related lands" (Columbia-North Pacific Technical Staff, 1970b), compiled largely by G. L. Bodhaine and M. J. Mundorff. The reader is referred to the latter report, especially, for subregional summaries of ground-water resources and conditions, including the types and productivity of water-bearing rock materials in the different parts of the region.

The present report is designed to be a regional part of a broad-perspective analysis by the U.S. Geological Survey of the ground-water resources of the nation. This part, previously designated the Columbia-North Pacific Region and now designated the Pacific Northwest Region, is shown in figure 1. This region includes all the Columbia River drainage basin in the United States, the drainage areas of coastal streams in Oregon and Washington, and the closed basins in south-central Oregon. This region of about 274,400 square miles (271,430 mi^2 of land and 2,980 mi^2 of water) comprises all of Washington, most of Idaho and Oregon, parts of Montana, Nevada and Wyoming, and a very small part of Utah. It is bounded on the east by the Rocky Mountains, on the north by the Canadian border, on the west by the Pacific Ocean, and on the south mainly by the California and Nevada state lines and the Snake River drainage divide. (See also fig. 4.)

THE CHALLENGE OF MEETING FUTURE WATER REQUIREMENTS

The requirements for water in the Pacific Northwest Region are increasing, and will become a progressively greater challenge to water-management skills and regulatory innovation. For a variety of reasons, the ground-water resources seem destined to play an increasing role in meeting the future water requirements.

PROJECTIONS OF WATER NEEDS

Projections of future water needs in various parts of the region are available from the report of the "Columbia-North Pacific Region Comprehensive Framework Study of Water and Related Land," by the Columbia-North Pacific Technical Staff—hereafter shortened to CNPTS (1972). Those projections are summarized in figure 2, along with compilations of water use during 1970 and 1975 obtained by canvass of water managers and others (Murray and Reeves, 1972, 1977). As shown in the figure, total water diversions and withdrawals are strongly dominated by irrigation requirements, and these requirements are expected to dominate in the future, also. The water withdrawn for irrigation in 1970 was about eight times greater than the combined withdrawals for industrial, municipal, and rural-domestic uses. As projected, water for irrigation would still represent the dominant need by 2020, amounting to about 85 percent of the total diversions within the region (fig. 2). The projected irrigation requirements by 2020 would represent a nearly 90-percent increase over the 1970 diversions for that use and would be equivalent to about 20 percent of the total stream discharge from the region (fig. 3).

The projections of irrigation water needs in figure 2 include not only diversions to irrigate cropland and pasture, but also water for nonfarm irrigation (such as parks, golf courses, and cemeteries), and a predicted need for irrigation of forest crops. Expected irrigation of forest lands will constitute an essentially new type of irrigation need, based on predictions of an increased wood-fiber demand and downward trend in future amounts of natural forest land. Irrigation to assure tree survival during the early years and to establish forests on dry or marginal lands is seen as one way to maintain or even increase wood-fiber yields from the region (CNPTS, 1971c, p. 28). Estimates in the

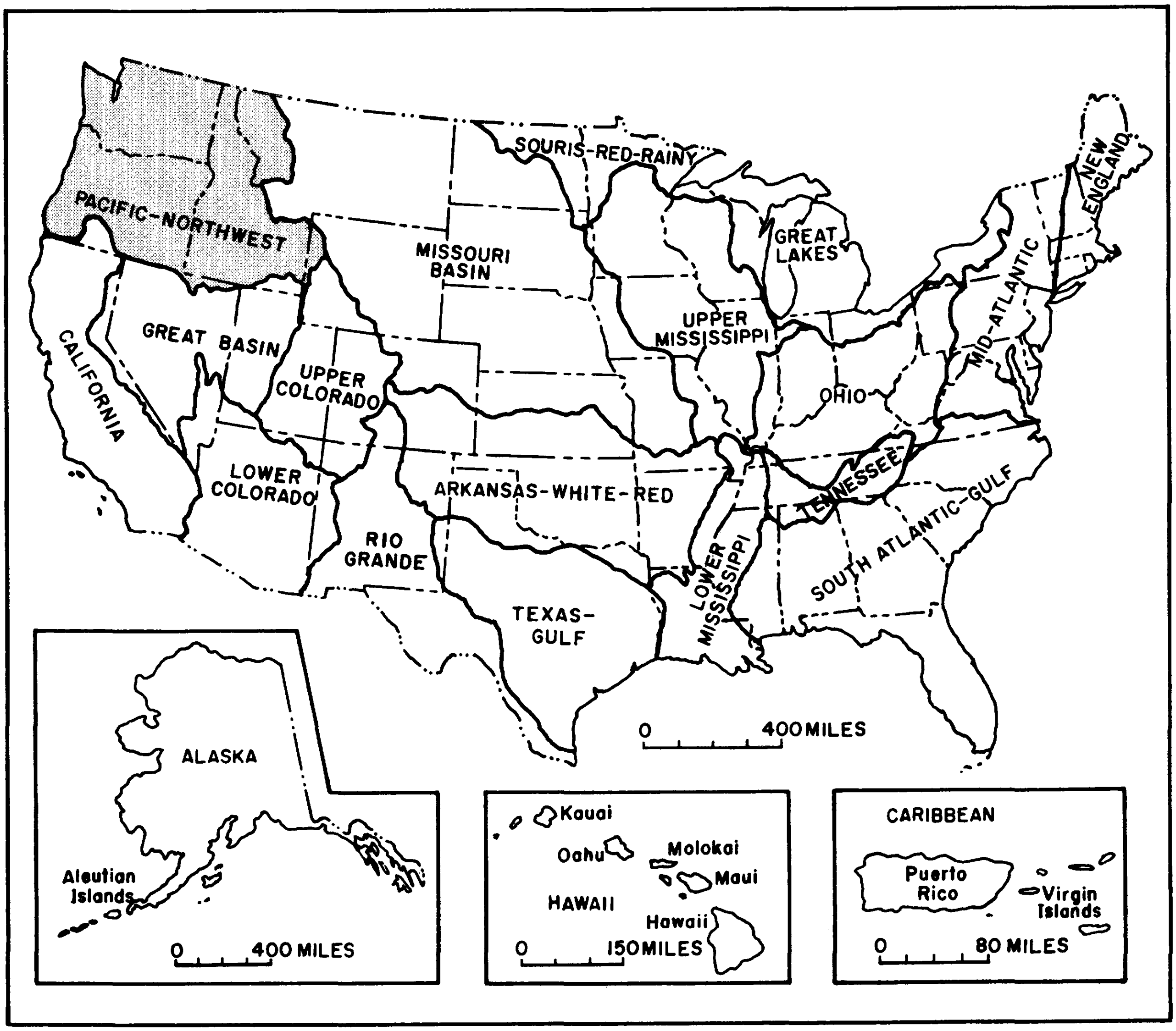


FIGURE 1.—Map showing the Pacific-Northwest Region and other regions of similar ground-water appraisals.

"framework" study indicate that roughly 5 million acres of forest land in the region might respond favorably if water were available.

Industrial and municipal water requirements, which constituted 6 and 4 percent respectively of the total withdrawals in 1970, were projected (fig. 2) to increase at rates much greater than the irrigation requirements. By the year 2020, needs for industry were expected to increase nearly 170 percent, and those for municipal supplies by more than 160 percent over the 1970 amounts. Even after those sizeable increases, however, the industrial and municipal water needs would amount to only 8 and 6 percent respectively of the projected total by 2020. Future needs for industrial and municipal water supplies are expected to be greatest in areas where these uses are already concentrated—namely, the Willamette-Puget Sound Trough and the vicinities of metropolitan centers throughout the rest of the region.

Rural-domestic water requirements were expected to grow generally apace with the projected total increases, remaining at less than 1 percent of the totals.

Sizeable demands for water that were not foreseen in the "framework" study may develop in the region, such as water for processing and transport of coal or other new uses associated with energy production. However, the needs for such purposes are expected to be restricted to only a few parts of the region, and the total of such unforeseen demands is expected to be relatively small.

The projections of water requirements (fig. 2), like all projections, are based on certain assumptions. Some of

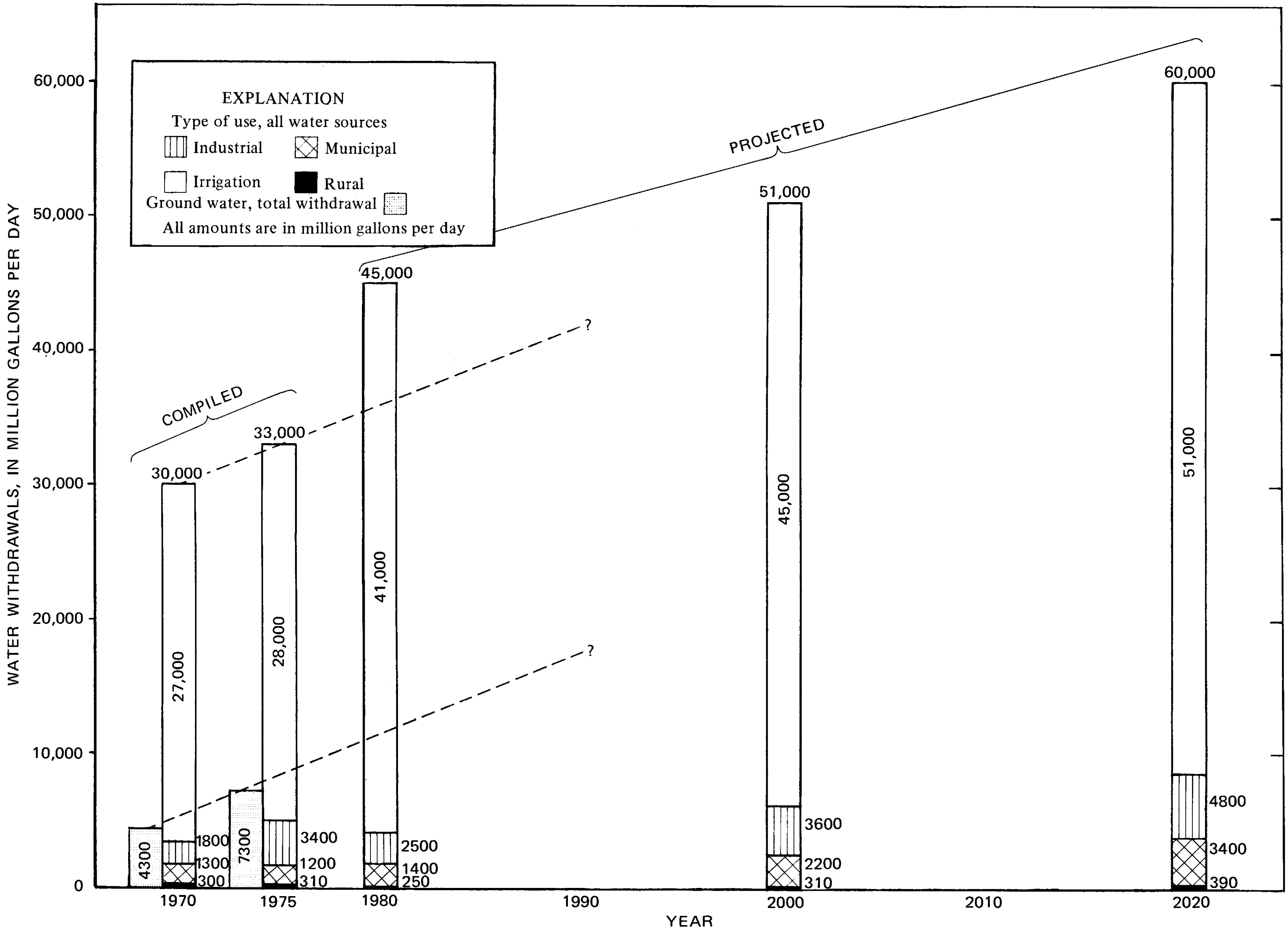


FIGURE 2.—Pacific Northwest water withdrawals compiled by U.S. Geological Survey for 1970 and 1975 and those projected by Columbia-North Pacific Technical Staff for 1980, 2000, and 2020. Sources: For 1970, Murray and Reeves (1972); for 1975, Murray and Reeves (1977); for 1980–2020, CNPTS (1972). Possible differences in reporting for the categories shown here as "municipal" and "rural" have no significant effect on the indicated relationships. Withdrawals for power generation are not included.

these are discussed in appendix 6 of the "framework" study report (CNPTS, 1971a, p. 5, 6). Most of the assumptions involved extension of socioeconomic conditions that prevailed prior to about 1965. The assumptions do not take into account certain shifts away from some earlier trends during the decade 1966–75, especially in the last half of the decade. Also, significant international events and shifts in national policies have occurred which, along with changes in socioeconomic trends, probably will affect future water requirements in the region.

Although a detailed analysis of the earlier assumptions and subsequent departures from them is beyond the scope of this report, certain near-term probabilities seem fairly obvious. These include a general slowdown in population growth, domestic commerce, and industry below the assumed trends for the region, with attendant slowing of related water needs.

Future energy sources and the fate of industries dependent upon them seem uncertain. The major industries are agriculture and food processing, lumbering and forest products, services (including tourism), minerals, metals, chemicals, and manufacturing. Some industries doubtless will be affected adversely, but deployment of industry (for environmental, energy, or other reasons) may create unexpected demands for water supplies at various places.

In judging the continued usefulness of the water-need projections from the "framework" study (fig. 2), requirements for irrigation are the key factor. In 1970 about 7.5 million acres were irrigated—roughly one-third of the total crop land at that time. The Snake River Plain accounted for more than half the total irrigated acreage, and the Columbia Plateau accounted for the second greatest fraction. Sizeable acreages are irrigated in all major parts of the region; even the farms in the more humid parts west of the Cascade Range can produce more and better crops with timely irrigation. About one-fourth of the land irrigated in 1970 reportedly had late-season water shortages. The dry lands that were classed as potentially irrigable totaled some 33 million acres, more than 40 percent of which were judged capable of producing high yields of climatically adapted crops (CNPTS, 1972, p. 85). Irrigated land was forecast to increase by 6 million acres, reaching a total of 13.5 million acres by 2020—still only one-third of the total irrigable land in the region.

The projected growth trend in irrigated farming also seems likely to be affected by counteracting influences. The depressing effects of economic slowdown, reduced population growth, and sharply higher farming expenses may be largely offset, or even dominated, by the spurring effect of strong export markets for farm products. Conversely, rising energy costs seem likely to constrain large-scale water withdrawals that involve high pumping lifts.

A comparison of water withdrawals in 1970 and 1975 (fig. 2) provides some insight into the durability of the projections for later years, although the extrapolations of a trend based on withdrawals for only those two years is tenuous, at best. A linear projection of the increase in withdrawals between 1970 and 1975 (upper dashed line in fig. 2) suggests that the total withdrawals by 1980 will fall far short of the projection for that year. This is not surprising, inasmuch as that forecasted growth in withdrawals would have required "a decade of unprecedented irrigation development during the 1970's" (CNPTS, 1971a, p. 45). Beyond 1980, however, the 1970–75 trend line is aimed generally toward the tops of the bars representing total withdrawals for 2000 and 2020; this trend line therefore suggests that the earlier forecasts of total withdrawals (largely irrigation withdrawals) for those years are still reasonable.

There are other reasons to expect that the projected needs for irrigation water by the years 2000 and 2020 may still be reasonable even though the needs for 1980 were overestimated in the earlier analysis:

1. The strong advantages that irrigation provides in the farming of the Pacific Northwest Region;
2. exports apparently will need to be maintained at high levels to offset U.S. purchases of foreign petroleum and other products;
3. worldwide needs for food and fiber resources continue to grow;
4. increased opportunities for international commerce with Communist-bloc nations including broadened markets for food and fiber products from the region.

Although irrigation use by 1980 apparently will fall far short of the projected amount, the withdrawals for nonirrigation uses in 1975 (fig. 2) had already exceeded the projections for 1980, owing largely to a 90-percent increase in withdrawal by industries.

In the aggregate, the water-need projections from the "framework" study seem to provide adequate guidance for the present study with regard to the general magnitude of future additional water requirements. Because of the aforementioned changing conditions that were not foreseen at the time the projections were made, the estimates of region-wide requirements by 2020 may be somewhat less reliable for the industrial and municipal categories than for the irrigation and rural-domestic categories.

SIGNIFICANCE OF GROUND WATER IN THE REGIONAL WATER SUPPLY

The Pacific Northwest Region's ground-water system may be thought of as a series of separate reservoirs, the upper parts of which are intersected by the surface-water system. The upper few hundred feet of the ground-water reservoirs serve the essential functions of moderating streamflow and sustaining the dry-weather flow of streams, feeding springs, and supplying water for most wells. Water in the deeper parts of the ground-water system is less available for use at present; however, the deeper zones may become very important in the future for subsurface disposal of wastes or as more water is required.

Ground water is by far the largest part of the region's freshwater resource, although most of it is hidden. Ground water fills the pore spaces and crevices in rock materials beneath all parts of the region down to depths of many thousands of feet. Very deep lying ground water, however, is commonly salty and is costly to extract because the rock materials at depth tend to have low permeability, or hydraulic conductivity. Furthermore, the renewability of the deep ground water is generally very limited; because of the low conductivity, water moves very slowly underground and commonly must move considerable distances from sources of replenishment at or near the land surface. Even discounting the very deepest water, however, the amount of fresh ground water in storage in the upper 1,000 feet of saturated rock materials is estimated to be about 160,000 billion ft^3 (cubic feet) or more than 13 times the average yearly outflow from the region through streams, which is about 12,100 billion ft^3. For a variety of reasons, not all this fresh ground water can be considered available for man's uses; the estimated amount of fresh ground water in "recoverable" storage at any time probably is on the order of 24,000 billion ft^3 (CNPTS, 1970b, p. 85), or about double the average yearly stream discharge from the region. The ground water receives an estimated 100 million acre-feet (CNPTS, 1970b, p. 89), or about 4,000 billion ft^3, of annual recharge, most of which ultimately discharges to streams and becomes part of the stream discharge. The estimated amounts of inflow to, and outflow from, the region are shown in relation to ground-water storage in figure 3.

The ground water and surface water are inseparable parts of the region's hydrologic system, with good hydraulic interconnection in many areas. This continuity between the ground water and surface water provides opportunities for greater beneficial use of the water resources but, at the same time, makes efficient management of the resources a difficult task under prevailing water laws, which tend to treat each of these two phases of water occurrence separately. Although greater utilization of the ground-water reservoirs cannot add to the total water supply (the inflow amounts in fig. 3), it can increase the dependability and the proportion of the total supply that is available for man's use. The improvement in dependability accrues through greater use of the reservoir function of the ground-water system. The increase in available supply results from the salvage of water that otherwise would evaporate or discharge naturally without being put to beneficial use. In contrast to these benefits, greater use of the ground water depletes the total water supply only to the extent that additional water from underground evaporates or is transported outside the region or area of management.

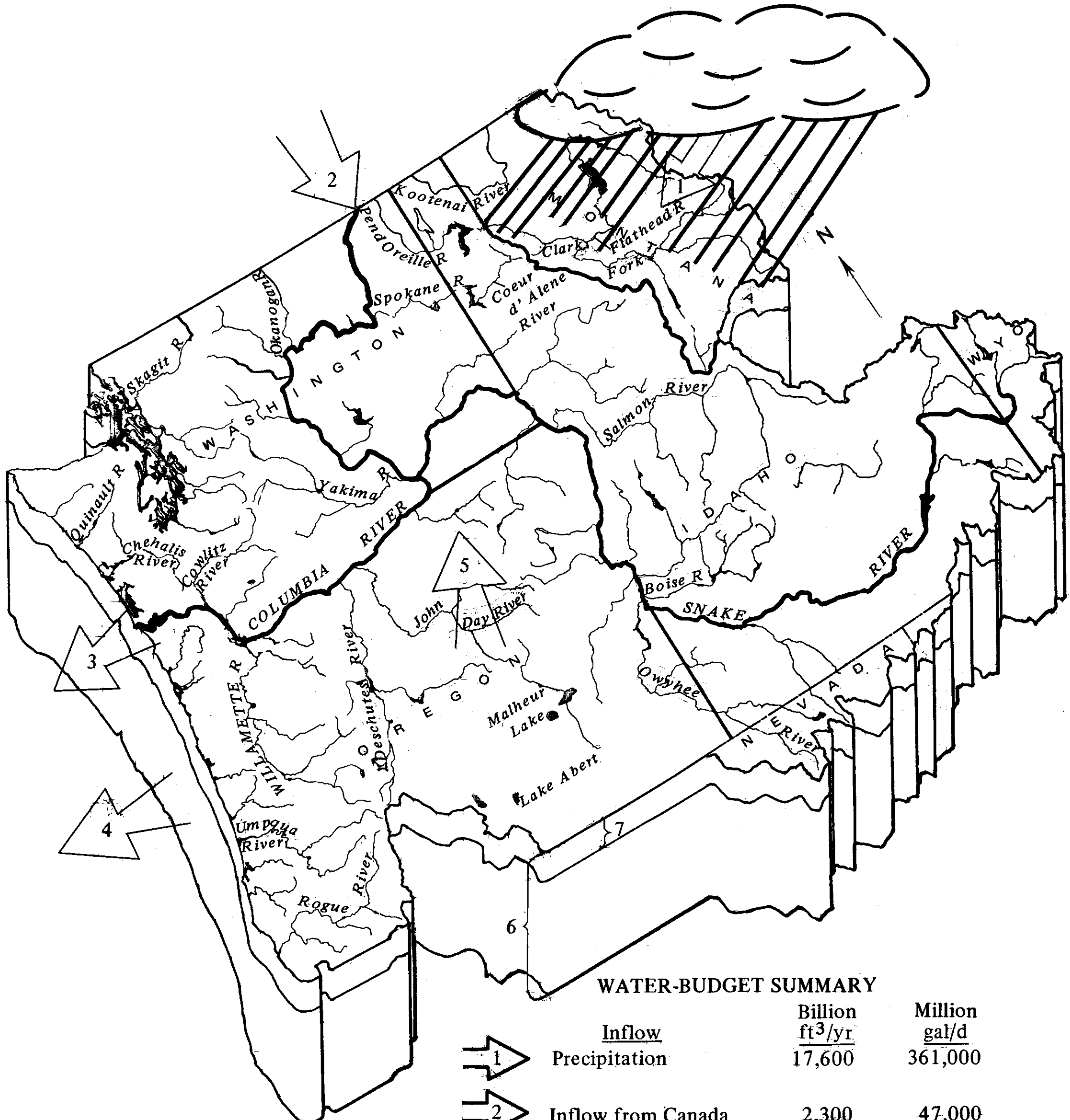
The available ground water is not evenly distributed throughout the region, as is shown schematically in figure 3, but varies greatly in availability from place to place. Ground water can be obtained nearly every place in the region, but at some places the quantities obtainable from a well are small. Also, in some areas a well must be more than 1,000 feet deep to obtain a dependable water supply. As stated by Mundorff (CNPTS, 1970b, p. 69),

> About 42 percent of the region is underlain by aquifer units with low porosity or permeability that generally will yield only small supplies of ground water. It is fortunate that these units are confined mainly to thinly populated (mostly mountainous) areas where water needs are comparatively small and surface-water supplies are plentiful.

The ground-water reservoirs that are most important in resource-management considerations are those capable of yielding water to wells at moderate or large rates and, therefore, which are large enough to be of public significance. Discussions in later sections of this report emphasize the major ground-water reservoirs that comprise the more extensive and productive aquifers in the region.

Up to the present time, man's use of the ground-water resources in the Pacific Northwest Region has been relatively small in comparison with the total amount available, and use of the ground-water reservoirs must increase greatly if the projected water needs (fig. 2) are to be met fully (or even largely) in the future. The average regionwide rate of ground-water withdrawal in 1975 was estimated to be about 7,300 Mgal/d of which about 4,500 Mgal/d were for irrigation and 2,800 Mgal/d for municipal, industrial, and rural water supplies. The ground-water withdrawal during 1975 constituted about 22 percent of the 33,000 Mgal/d diverted and withdrawn for all the uses listed in figure 2.

From 1970 to 1975, the withdrawal of ground water apparently increased by the largest amount in the history of the region. The estimated increase was 70 percent of the 1970 amount of 3,000 Mgal/d—the same as



WATER-BUDGET SUMMARY

	Billion ft^3/yr	Million gal/d
Inflow		
1 Precipitation	17,600	361,000
2 Inflow from Canada	2,300	47,000
Totals (rounded)	20,000	410,000
Outflow		
3 Stream discharge	12,100	248,000
4 Ground-water discharge to saltwater	300	6,000
5 Evapotranspiration	7,600	156,000
Totals (rounded)	20,000	410,000

GROUND WATER IN STORAGE

	Billion ft^3
6 Total in upper 1,000 feet	160,000
7 Amount "recoverable" (fraction of total–not intended to show depth of wells)	24,000

FIGURE 3.—Generalized water budget and volumes of groundwater in storage for the region (data largely from Columbia-North Pacific Technical Staff, 1972, and appendices).

the increase in total withdrawal from all freshwater sources (fig. 2). The difference in indicated withdrawal rates apparently represents a legitimate, generally progressive increase during the 5-year period rather than an anomalous difference caused, for example, by drastically different amounts of rainfall during the irrigation seasons in the two years. Most of the increase was in Idaho, including shift of about 1,400 Mgal/d of irrigation withdrawals from surface-water to ground-water sources, and an increase of more than 1,500 Mgal/d in withdrawals by self-supplied industries.

Further increases in use of the ground-water reservoirs in the region seem inevitable for several reasons:

1. The dry-season flows of most streams east of the Cascade Range are fully appropriated (some are overappropriated).
2. Most cost-effective surface reservoir sites already have been used; therefore, further deliberate storage of water for later utilization must be largely in the ground-water reservoirs.
3. As ground-water information and water-management techniques develop further, management of the stream systems and ground-water reservoirs conjunctively will become more practical and effective.

Even in cases where choices exist, use of ground-water reservoirs has important advantages over use of surface-water reservoirs. For example, the initial costs connected with management of subsurface reservoirs commonly are much lower than for surface-water reservoirs. Also, ground-water bodies are less subject to evaporation, pollution, and temperature changes, and do not present hazards of downstream flooding.

GEOGRAPHIC FACTORS AFFECTING THE GROUND-WATER RESOURCES

Because the distribution, availability, and abundance of ground water in the Pacific Northwest Region are largely controlled by the landforms, climate, and earth materials, a general understanding of these features is necessary as a foundation for more specific discussions of the ground-water resources.

If one word could be used to describe the geography of the Pacific Northwest Region, that word probably would be "variety." The region is a composite of contrasts in physical and cultural geography. In population it ranges from dense urban centers, such as Seattle and Portland, to large tracts of land with no permanent human inhabitants. Its climate is dominated mostly by marine air masses but at times is influenced by continental air. It includes the wettest spot in the 48 conterminous states and some of the driest places in the Nation. The region contains examples of most of the landforms known to man, at altitudes ranging from sea level to more than 14,000 feet. Its vegetation assemblages range from rain forest to alpine to desert. It is not surprising, therefore, that great variety exists in the availability of and needs for the region's water resources, including its large and valuable ground-water resources.

LANDFORMS AND DRAINAGE

The landforms of the Pacific Northwest Region largely control the availability and use of ground water as well as the patterns of replenishment from precipitation and of drainage. The features of greatest significance to this ground-water appraisal include: The mountains, which receive much of the precipitation and divide the region into climatic zones; the flatter lands—valley floors, plains, and plateaus—which contain most of the population and account for most of the ground-water use; and the streams, which variously recharge or drain the ground-water reservoirs. The general physiographic divisions of the region are shown in figure 4. Detailed discussion of the physiographic features is beyond the scope of this report but can be found in CNPTS (1970b) from which this figure was taken.

One important feature of the landforms that is not shown in figure 4 is the altitude of the flatter lands. The altitude strongly influences the growing season which, along with other factors such as soil productivity and growing-season precipitation, largely controls the demands for irrigation water. In order of increasing altitude, the areas of extensive flatter land labeled in figure 4 are: Willamette-Puget Sound Trough (most populous part), Columbia Plateau, Snake River Plain, and Oregon Closed Basins. At the two extremes, the Willamette-Puget Sound Trough has much land below the 500-foot altitude and an average growing season commonly greater than 160 days per year; the Oregon Closed Basins area has much land above 4,000 feet where frost may occur during any clear night of the year. The Columbia Plateau and Snake River Plain are intermediate in growing season as they are in altitude.

PRECIPITATION AND REPLENISHMENT PATTERNS

Precipitation over the Pacific Northwest Region (fig. 5) is the ultimate source of all the water except inflow from Canada. The characteristics of the precipitation (mainly the rates, seasonal distribution, and amounts as rain and snow) control the water that is available to recharge (replenish) the ground-water reservoirs, either by direct infiltration at the land surface or by seepage from streams. The actual recharge from precipitation, of course, is also controlled by other factors, principal of which are the character of the soil and of the rock materials that constitute the ground-water reservoirs.

The most abundant annual precipitation in the conterminous 48 States occurs at high altitudes in the Olympic Mountains (northern part of Coast Range, fig. 4), where it exceeds 200 inches. Eastward from the crest of the Olympics and the coastal mountains to the south, precipitation decreases to about 35 inches along the Willamette-Puget Sound Trough, then rises to 120

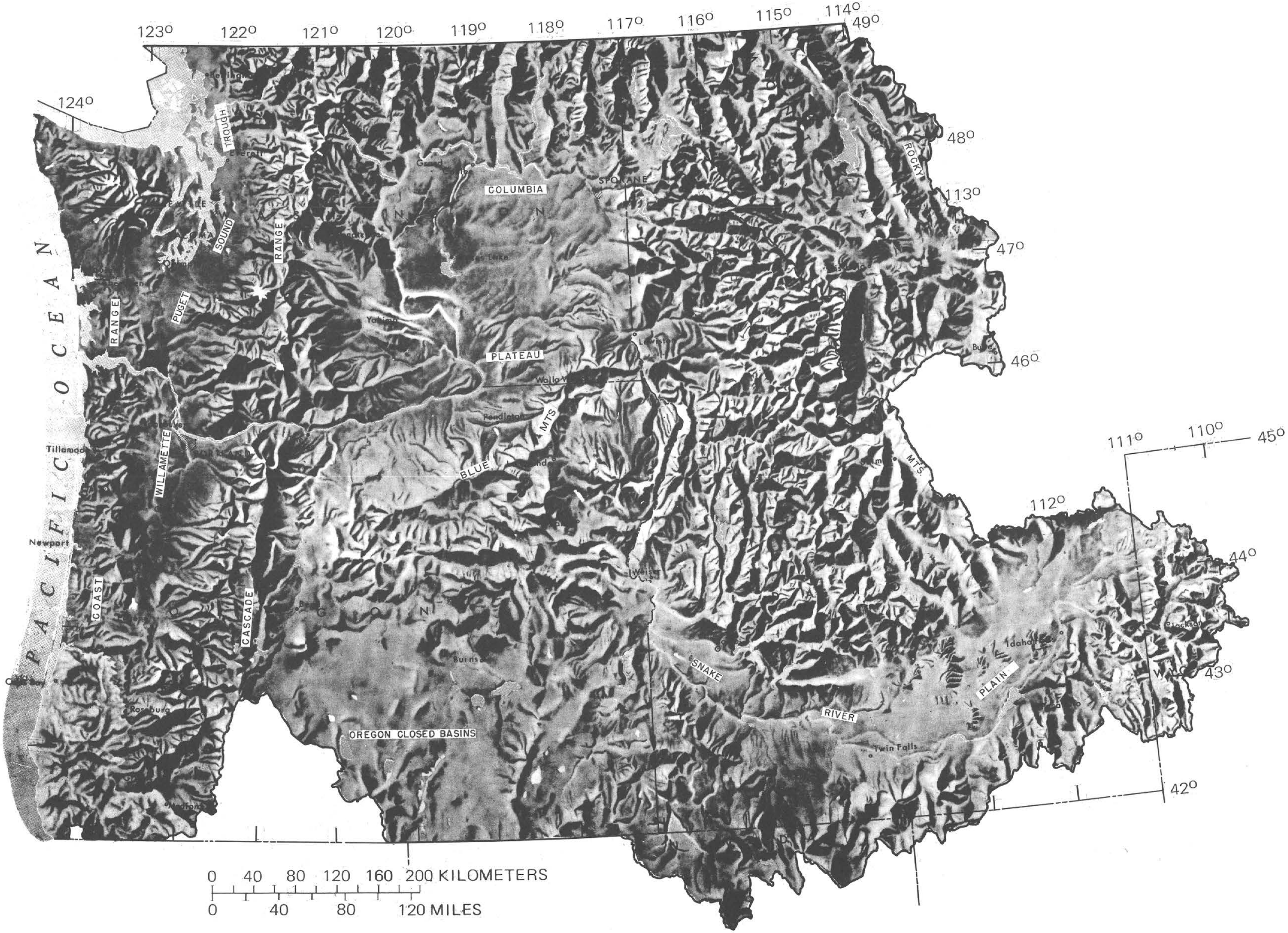


FIGURE 4.—Major land and water features of the region (Columbia-North Pacific Technical Staff, 1970b, fig. 2).

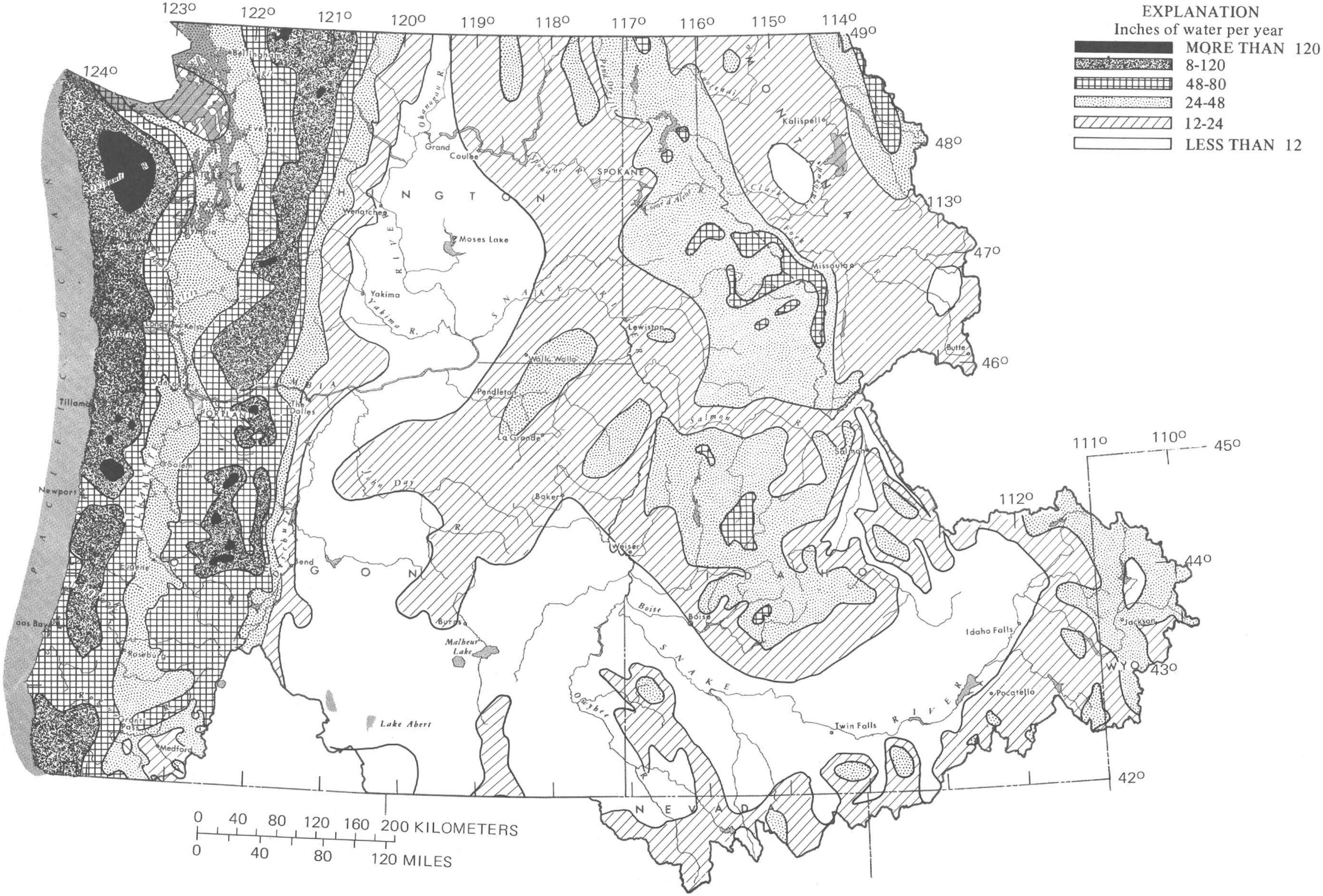


FIGURE 5.—Generalized distribution of annual precipitation in the region (adapted from Columbia-North Pacific Technical Staff, 1970b, fig. 3).

inches or more toward the crest of the Cascade Range.

East of the Cascade Range in Washington and Oregon the annual precipitation decreases sharply to about 10 inches or less in the valleys and on the plateaus, but generally increases again toward the east, where it reaches 40–50 inches in mountain areas.

The Snake River Plain receives from 6 to 15 inches of annual precipitation, and mountains surrounding the plain receive as much as 40 inches. In northern Idaho annual precipitation ranges from about 16 to 70 inches. Western Montana receives about 12 inches per year in some intermontane valleys but more than 150 inches at places in Glacier National Park (too small to show in fig. 5). Relatively dry belts exist in the rain shadows of the mountain ranges, and the greatest precipitation generally falls on the western, windward slopes.

Extreme variations occur in the distribution of annual runoff in the region. In the western part, large amounts of precipitation generate an average annual runoff that exceeds 100 inches in a substantial area of the Coast and Cascade Ranges. In contrast, annual runoff averages less than 1 inch in much of eastern Washington, eastern Oregon, and southern Idaho. Annual runoff greater than 40 inches is rare east of the Cascade Range. Patterns and amounts of runoff in various parts of the region are further described in CNPTS (1970b).

In areas receiving less than 12 inches, much of the precipitation water is likely to run off or evaporate soon after it falls or, if it infiltrates below land surface, to be held in the soil and be used up by vegetation. In these areas, the amount of precipitation that percolates down to the ground-water system probably is equivalent to less than one inch of rainfall except where the infiltration capacity of the soil or rocks at land surface is unusually favorable. Where infiltration is poor, and in some drier areas, precipitation might recharge the ground water only during unusually wet periods.

In areas shown as receiving less than 12 inches of precipitation per year (about 27 percent of the region), crops generally cannot be grown without irrigation. Exceptions occur in some areas that are subirrigated by shallow ground water, and in areas that are too small to be differentiated in figure 5 and which have slightly greater precipitation. Also, at places where soil conditions are especially favorable in depth and texture to store the moisture, dry-land farming practices have evolved which allow successful production of grain crops in alternate years on land that apparently receives only 10–12 inches of precipitation per year. In general, where soil and other conditions are favorable for farming, these areas potentially would benefit most of all areas in the region from the availability of water for irrigation.

The areas receiving 12–24 inches (about 34 percent of the region) are intermediate in regard to potential recharge for ground water and water needs for farming. The places that receive precipitation amounts in the upper part of this range (generally closer to the higher-precipitation areas in fig. 5) commonly have a few inches potentially available for recharging the ground water. Actual recharge is more likely to be limited by land slope and infiltration capacity of soils rather than by precipitation amounts. In these places, crops that can be grown by dry-land farming methods are somewhat more varied and considerably more dependable and productive than in drier areas.

Areas receiving more than 24 inches of precipitation per year may be generally considered to have abundant water available at the land surface for recharging the ground water. Some of these areas, including lowland parts of the Willamette-Puget Sound Trough and the floors of many smaller valleys, are underlain by permeable rock materials and receive large amounts of recharge. However, in some of the areas of abundant precipitation, actual recharge may be insignificant. Many of these areas, especially east of the Cascade Range, consist of mountains where the combination of steep slopes and soils of low permeability induces a large proportion of surface runoff from the precipitation. (Compare figs. 4 and 5.) Therefore, except in areas of permeable rocks in the high Cascades of Oregon and southern Washington (the High Cascades ground-water reservoir, table 1 and fig. 8), the local recharge in the mountainous areas of abundant precipitation is relatively unimportant to the manageable parts of the regional ground-water resources. Also, for several reasons including rugged terrain, generally poor or absent soils, and available surface water, the higher areas of abundant precipitation generally do not require additional ground water for irrigation or other purposes. The higher areas of abundant precipitation are significant to the management of ground-water mainly in that they generate stream runoff which flows to lower, generally drier parts of the region and contributes to the recharge of major ground-water reservoirs located there.

The seasonal distribution and type of precipitation also affect the availability of water and opportunity for recharge of the ground water. Although average yearly precipitation ranges widely, the seasonal distribution of precipitation is similar throughout most of the region. Except for parts of western Montana and north-central and southeastern Idaho, the region has distinctly dry summers and wet winters. About one-third, or less, of the annual precipitation generally occurs during the 6-month period April-September, and less than 15 percent during the latter 3 months of that period (fig. 6). About two-thirds occurs during October-March, when it generally falls as rain at the lower altitutdes and as snow at the higher altitutdes. Abundant snow on many of the high mountains has maintained glaciers and perennial snowfields that are important sources and regulators of streamflow. The heaviest annual snowfalls—sometimes totaling more than 60 feet—are in the higher parts of the Cascade Range. In most mountain areas at altitudes above 6,000 feet, snow cover commonly persists from early November until early June. Melting of the abundant snow maintains flow at relatively high levels in many of the streams throughout the spring; in some places the high flow does not end until early July.

At the stations shown in figure 6, precipitation is greatest during the winter but differs significantly in amounts. Astoria, Oregon, receives 13 times as much precipitation in December as does Yakima, Washington. In some eastern parts of the region, however, the seasonal distribution of precipitation is different, and

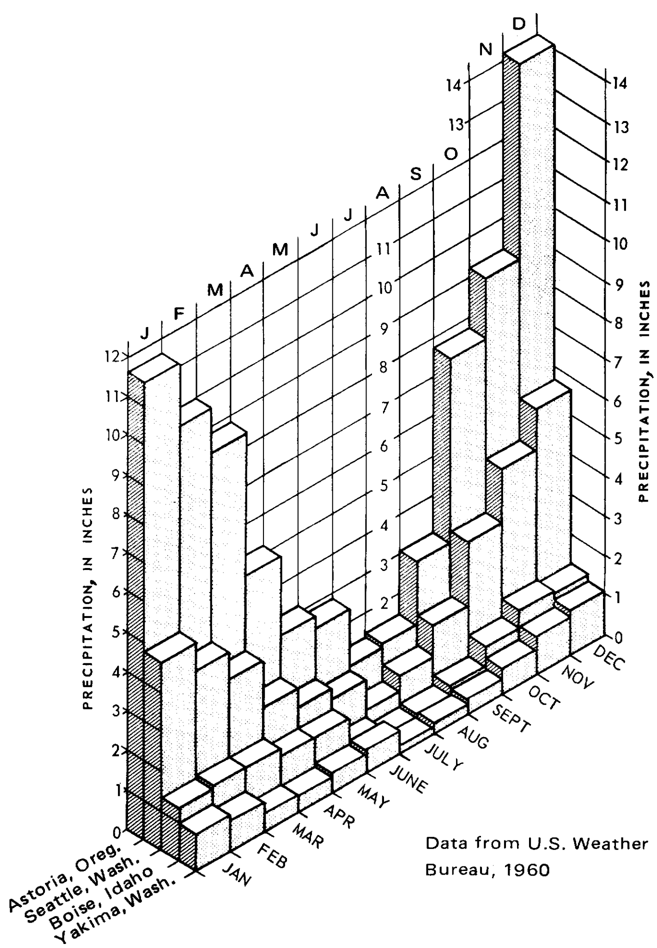


FIGURE 6.—Seasonal distribution of precipitation at selected weather stations in the region (Bodhaine and others, 1965, fig. 8).

the differences between amounts during the summer and winter are generally less distinct. At some lowland precipitation stations in western Montana and north-central and southeastern Idaho more than one-half the annual precipitation falls during the period April-September.

The coincidence of the wettest period with the cooler, nongrowing season is highly favorable for recharge to the ground-water reservoirs. During the cooler months, the losses of precipitation to evaporation and vegetation are minimal, and the opportunity for available water to infiltrate the land surface is greatly enhanced. Conversely, the small percentage of precipitation that arrives during the growing season causes greater water needs for irrigation and summertime municipal uses than would occur in comparable situations in most other regions of the Nation. The distinctly dry summer period is the reason why even the crops grown west of the Cascades benefit greatly from irrigation.

Evaluation of the supplies of water that can be expected in the future, and of future water needs as well, must include the possibility of protracted periods of drought or above-normal precipitation. Previous analyses of long-term variations in precipitation, including determination of prehistoric climatic trends based on tree growth rings, have yielded the following conclusions (Bodhaine and others, 1965, p. 31):

1. Periods during which precipitation will be considerably above or below the average for several successive years can be expected occasionally in any part of the region.
2. The cumulative effects of several closely spaced periods of deficient or abundant precipitation will be greatest in the drier parts of the region.
3. During the period 1287–1937, there was no persistent trend toward a wetter or drier climate in eastern Oregon.
4. Although significant variations of the climate (including precipitation) have occurred throughout much of eastern Oregon (and probably beyond), no rhythmic cycle was evident or could be predicted on the basis of tree rings.
5. A general drought in eastern Oregon, which began in 1918 and lasted until about 1940, was the most severe that the area had experienced during the 650 years prior to 1937.

One of the unstated assumptions related to the projections of future water needs (fig. 2) is that the patterns of precipitation will continue in the future about the same as those in the past.

GEOLOGIC SOURCES AND DISTRIBUTION OF GROUND WATER

THE PRODUCTIVE AQUIFERS

The main focus of this report is on the more than half of the Pacific Northwest Region that is underlain by rock materials known, or believed from geologic evidence, to be capable of yielding ground water to wells at moderate to large rates. These are the areas where proper planning and effective water management, based on adequate data and sound hydrologic principles, along with the removal of nonessential constraints, can produce a significant increase in the amount of water available for man's use. These are also the areas where the ground-water reservoirs are most likely to be economic sources of supplies for irrigation, industrial, and municipal uses.

The major ground-water reservoirs can be classified mainly in three groups—those made up of (1) predominantly sedimentary rocks (including deposits from streams, glaciers, and the wind), (2) predominantly volcanic rocks, and (3) combinations of sedimentary and volcanic rocks. The generalized distribution of these types of aquifers where they are capable of yielding 100 gallons per minute or more of water to individual wells (but without regard to depth of well or amount of pumping lift) is shown in figure 7.

Differences in the occurrence and movement of ground water in the two main classes of rocks—sedimentary and volcanic—are significant to the functions and management of these rocks as ground-water reservoirs. The sedimentary rocks yield water to wells mainly from layers of sand and gravel, which are the kinds of sedimentary rocks in this region that are most likely to yield water at moderate to high rates. Less permeable sedimentary materials, such as clay and silt, are more common in the region and, although they yield water to wells at lower rates, they serve the extremely valuable function of long-term storage that can drain slowly to adjacent permeable aquifers. These fine-grained deposits have a relatively high porosity, but the pore spaces are so small that considerable force (in the form of hydraulic pressure or weight of overlying rocks) is required to dislodge much of the water they contain. The saturated space within the permeable sedimentary rocks consists mostly of the primary pore space left between the particles of rock materials as they were deposited. Those sedimentary rocks in the region that have been hardened by such natural processes as compaction or cementation may develop secondary joints and fractures which transmit water, but the benefits of such secondary openings commonly do not offset the loss of pore space and permeability that results from the rock-hardening processes.

The volcanic rocks yield water mainly from permeable zones that occur at or near the contacts between some flow layers; central and lower parts of the flow layers are nearly always denser and much less permeable. The abundance, causes, and nature of the permeable zones differs greatly. The zones tend to occur less commonly in rocks of the Columbia Plateau (fig. 4) than in rocks of the Snake River Plain and younger volcanic rocks. (See table 1, "Remarks".) They commonly result from the incomplete filling of openings at the top of one flow layer (such as rubble, cinders, or scoria) by the lava of a succeeding flow. Other permeable interflow zones have other origins, including deposition of sedimentary materials during the times between lava outpourings.

The volcanic ground-water reservoirs commonly yield water to wells at high rates but generally can yield less water from storage than the same volume of permeable sedimentary rocks. This is because the total volume of openings in the volcanic rocks is nearly always less than that in productive sedimentary rocks; moreover, many openings in the volcanic rock are likely to be poorly connected.

Both the sedimentary and the volcanic reservoir rocks are layered and, consequently, movement of water through the rocks along the beds (mainly horizontal) is less restricted than movement across the beds (mainly vertical). In the sedimentary reservoirs, vertical movement between the permeable beds (mostly sand and gravel) is commonly impeded by intervening layers of silt, clay, or naturally cemented materials. In the volcanic rocks, vertical movement is impeded by the dense and poorly permeable rock which generally constitutes the bulk of each flow layer. Even the dense parts of the flow layers, however, generally contain enough fracture and joint openings to allow some movement of water, although leakage from one permeable interflow zone to another may be greatly restricted. Cross-bed leakage between permeable zones in both the sedimentary and volcanic rocks is "short-circuited" by many wells that are either unlined (uncased) in the interval between permeable zones, or have casing that is open to more than one of the zones.

Some large bodies of the saturated permeable rocks shown in figure 7 are at such great depths, or in such high or rugged terrains, that imminent development is unlikely. However, at many places, as in the Cascade Range in Oregon and southern Washington, these remote aquifers are very valuable because of the large quantities of water they supply to streams. Also, some of these remote aquifers are likely to be future sources of water for increased forest irrigation, (See table 1, High Cascades ground-water reservoir.)

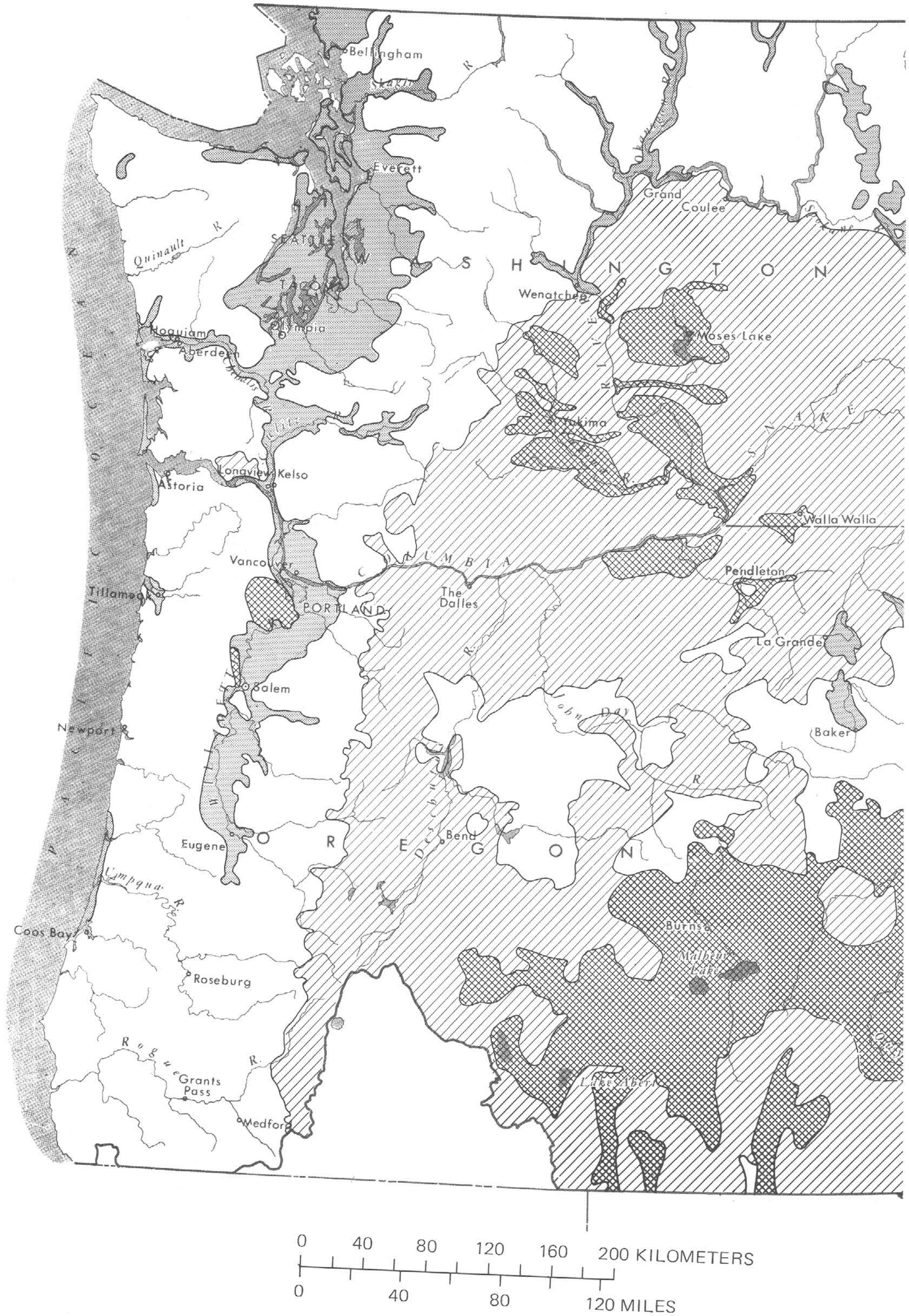
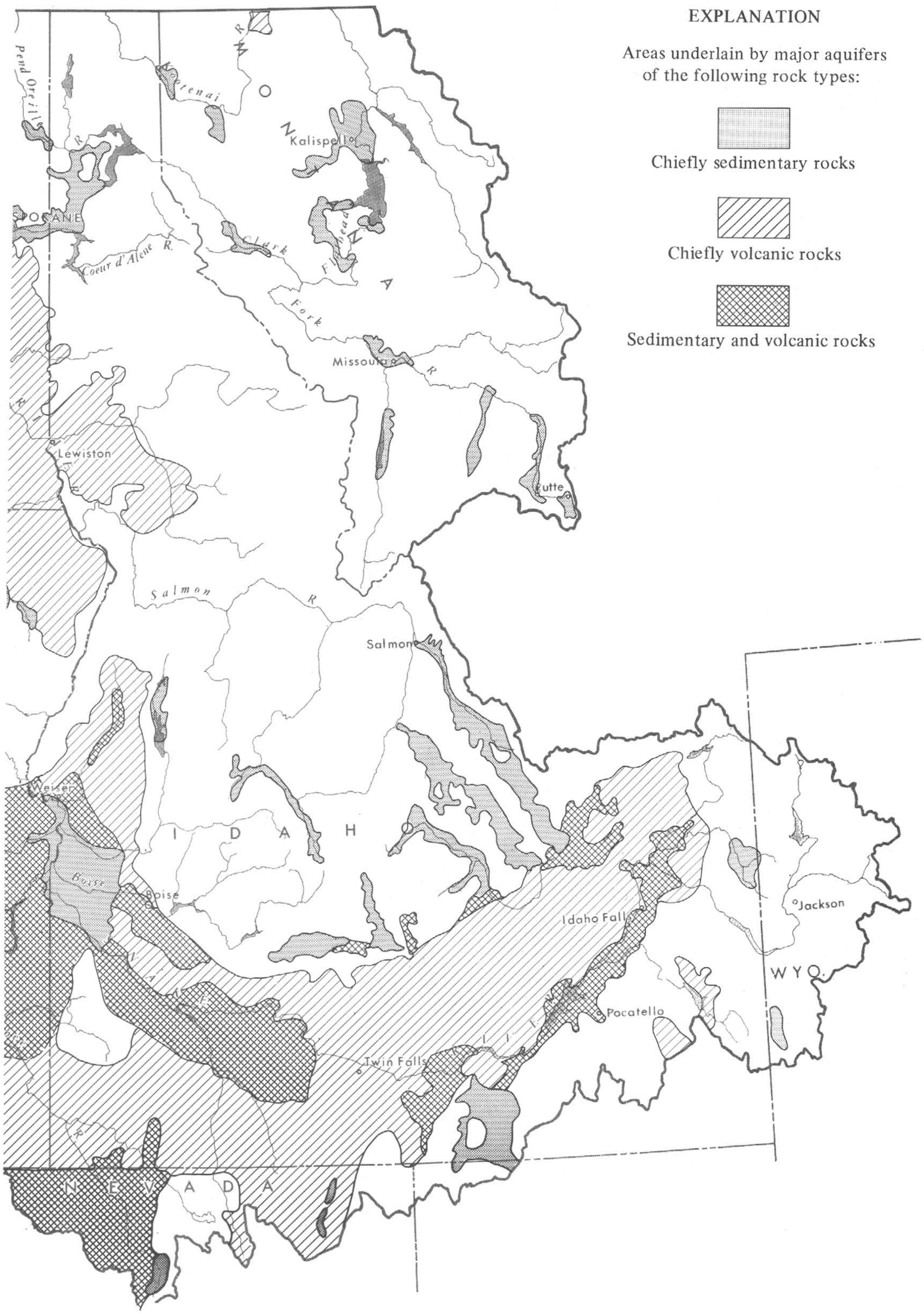


FIGURE 7.—Generalized distribution and types of major aquifers



(Columbia-North Pacific Technical Staff, 1970b, fig. 20).

DESCRIPTION OF THE GROUND-WATER RESERVOIRS

Extensive areas in the region are similar enough in climate, topography, water uses, and character of the aquifers to be considered as a unit for discussion of ground-water problems and management opportunities. Six such areas, referred to in this report as major ground-water reservoirs, are shown in figure 8. The general characteristics of these major ground-water reservoirs are summarized in table 1, along with associated problems and water-management opportunities.

The grouping of areas into the major ground-water reservoirs is not intended to imply that all parts of the designated reservoirs are hydraulically interconnected or can be managed as a unit, or that water necessarily moves across the state boundaries that cross some of the designated reservoirs. Unfortunately, the natural extent of these major ground-water reservoirs does not fit drainage-basin or other subregional boundaries and, therefore, the reservoir areas are difficult to relate to the summary values found in earlier regional reports. However, a few general statements can be made. For example, the major ground-water reservoirs probably receive more than one-half the estimated 4,000 billion ft^3 of annual recharge (p. 6); they contain about two-thirds of the region's ground water in recoverable storage (fig. 3), or 16,000 billion ft^3; and the ground-water withdrawal from them in 1970 (about 3,600 Mgal/d) accounted for more than four-fifths of the total for the region that year (fig. 2). More detailed information about various parts of designated reservoir areas is available in reports listed in "Selected References," especially in the aforementioned Appendix 5 of the "framework" study (CPNTS, 1970b). The notes in table 1 help relate the major ground-water reservoirs to the subregions used in that earlier study.

Besides those areas shown in figure 8, there are many smaller ground-water reservoirs in the region that are capable of yielding water at rates suitable for industrial, irrigation, and public supplies. Some of these, including scattered areas along the coastlines of the Pacific Ocean and along major streams, are shown in figure 7, but others are too small to be shown at the scale of that map. The smaller size of these ground-water reservoirs does not reflect their relative importance in the region; their aggregate volume is several hundred cubic miles, and at many places they are the only usable sources of fresh ground water. Moreover, they include some of the areas most likely to benefit from water-management possibilities. Therefore, although they are not listed individually in this report, they are included as a category in table 1 and are mentioned in the following summary discussions of ground-water problems and management opportunities. Some of these smaller reservoir areas were described in greater detail by Mundorff (CPNTS, 1970b).

MAJOR GROUND-WATER PROBLEMS

The most significant problems pertaining to ground water, which are listed briefly for each of the ground-water reservoirs in table 1, fall into five general categories. These are: (1) Progressively declining water levels; (2) ground-water quality problems; (3) water-logging; (4) inadequate information, and (5) competition for available supplies.

PROGRESSIVELY DECLINING WATER LEVELS

A decline in ground-water levels is an inevitable consequence of withdrawing water from wells—it does not necessarily represent a long-term depletion of the ground-water reservoir, otherwise called ground-water mining. The long-term significance of water-level declines depends on several interrelated conditions, among which are the year-to-year rate and persistence of decline, the size of the ground-water reservoir in relation to the area where the decline occurs, and the hydrologic and economic consequences of continuing decline. Short-term declines in levels can have beneficial water-conservation effects, such as the salvage of water otherwise lost as evapotranspiration from water-logged land, or creation of storage space in the ground-water reservoir for subsequent filling by surplus stream water. Even if water-level decline can be identified as a long-term depletion of a ground-water reservoir, the results may not be all bad, especially if there is no compelling reason to preserve the ground water and if undesirable consequences of the depletion (such as reduction of streamflow or ultimate disruption of local economy based on irrigation farming) can be tolerated. Each declining water level must be judged on its own special conditions.

Persistent declines of ground-water levels have occurred in several areas of the region, and major depletion of the ground-water reservoir has been projected for a few areas. The declines are all in areas of sizable pumping for irrigation, although pumping for municipal and industrial uses has contributed to the declines in some areas. Most of the declines involve the volcanic aquifers, and most are in the arid and semiarid parts of the region. Significant, persistent declines have occurred in the Willamette Valley, the High Desert, the Columbia Plateau, and the Southern Idaho major ground-water reservoirs shown in figure 8. Locations of the areas of decline are shown in figure 9, and information about the declines is summarized in table 2.

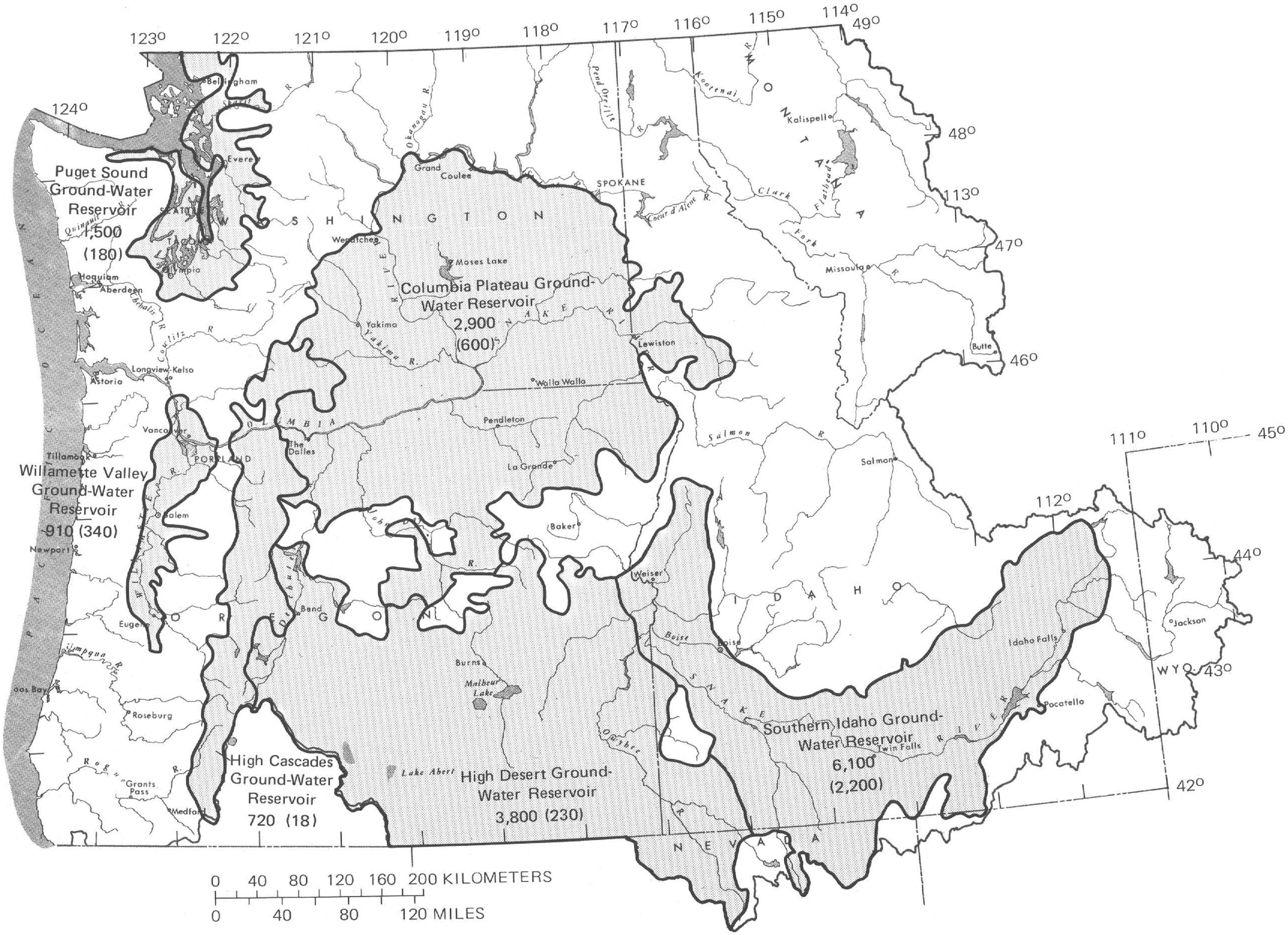


FIGURE 8.—Areas designated as major ground-water reservoirs, estimates of recoverable water in each (billion cubic feet), and 1970 pumpage (in parentheses—million gallons per day).

TABLE 1—*Summary of conditions in major ground-water*

Designation used in this report	Major aquifer[1] materials and yields to wells	Recharge to major aquifers	Discharge modes and withdrawal	Largest existing use of the ground water
Puget Sound ground-water reservoir[2]	Sedimentary rocks deposited by streams or glaciers; moderate to very large rates of yield.	Infiltration of precipitation and streamflow; generally ample in relation to pumpage.	Seepage to streams and marine waters; springflow along slopes. Pumpage is small in relation to recharge.	Public supplies, largely supplemental to stream supplies.
Willamette Valley ground-water reservoir[3]	Sedimentary rocks deposited by streams and glaciers and (in northern part) interflow zones in basalt; alluvial gravel along Columbia River has very large rates of yield.	Mainly by infiltration of precipitation water; flood waters from major streams recharge adjacent aquifers; irrigation augments natural recharge, Recharge generally ample, except for basalt aquifers.	Seepage to Columbia and Willamette Rivers and their major tributaries. Pumpage from sedimentary aquifers is small in relation to recharge.	Industrial supplies, mostly in metropolitan area near Columbia River,
High Cascades ground-water reservoir[4]	"Young" volcanic rocks; very large rates of yield.	Infiltration of precipitation water; recharge rates greatest of all the major ground-water reservoirs in the region.	Seepage to streams, which have very high dry-season flows, and springflow. Very little pumpage.	Rural domestic and stock supplies.
High Desert ground-water reservoir[5]	Sedimentary rocks deposited from streams and lakes; "young" volcanic rocks; older sedimentary and volcanic rocks. Rates of yield are moderate to very large.	Infiltration of precipitation and of runoff from mountains within and bordering the area. Away from the mountains, recharge may occur only occasionally.	Evapotranspiration, springflow, and (in northern parts of the area) seepage to streams. Pumpage very small in relation to ground water in storage and average recharge.	Irrigation.
Columbia Plateau ground-water reservoir[6]	Volcanic rocks of the Columbia River Group (and similar rocks in Oregon); alluvial deposits from modern streams and from Glacial-Age meltwater floods; older sedimentary basin-fill deposits. Rates of yield are moderate to very large.	Infiltration of rain and snowmelt water from land surface and stream channels; infiltration of irrigation water. Recharge in non-irrigated areas is limited by dry climate; recharge incidental to irrigation can be many times the natural recharge. At places, recharge probably occurs only during unusually wet periods.	Seepage to streams; springflow and seepage at land surface; evapotranspiration. Pumpage is generally small in relation to total recharge and amount of ground-water in storage, but tends to be concentrated.	Irrigation.
Southern Idaho ground-water reservoir[7]	Young basaltic volcanic rocks; young sedimentary deposits; older volcanic and sedimentary rocks. Rates of yield are moderate to very large.	Natural recharge is mainly by seepage from streams during their high-flow periods (especially streams that carry water into the area from adjacent uplands), and by direct infiltration of rain and snowmelt water. Water lost from the irrigation process is a large source of recharge, the largest source at places.	Springflow and seepage to streams; evapotranspiration; pumpage for irrigation is very large, but is causing water-level declines in only a few areas.	Irrigation.
Smaller ground-water reservoirs[8]	Mainly young sedimentary deposits (alluvial fan, floodplain, glacial outwash, and lake deposits; dune and beach sand); some volcanic rocks.	Infiltration of precipitation water; seepage from streams during their high-flow periods; seepage from irrigated soils and conveyance ditches.	Seepage to streams during their low-flow periods; evapotranspiration; springflow; seepage to the ocean. In relation to the amounts in the individual ground-water reservoirs, pumpage ranges from very small to large.	Generally irrigation.

NOTES: 1. Arbitrarily designated as capable of yielding water to a properly constructed well at a rate of 100 gpm or more, from a depth that is reasonable for common drilling methods and modern pumping equipment.

2. Lies entirely within Subregion 11 of the CNPTS study.

3. Comprises southern part of Subregion 8 and lowland parts of Subregion 9 of the CNPTS study.

4. Comprises mountainous parts of Subregions 3, 7, 8, 9, and 10 of the CNPTS study.

reservoirs (General location and extent shown in fig. 8)

Major problems pertaining to ground water			
Existing	Foreseeable	Management opportunities	Remarks
Troublesome amounts of dissolved iron in some aquifers; local deterioration of water quality resulting from waste-disposal practices; lack of adequate information in critical near-shore areas; seasonal waterlogging.	Continued local deterioration of water quality resulting from waste disposal; local salt-water intrusion resulting from increased near-shore pumping.	Reduction of pollution from surface or shallow waste disposal; greater use of ground water as supplies for near-shore development and for irrigation; use of deep, confined salty-water aquifers for waste disposal or storage of freshwater and natural gas.	Very large additional supplies of ground water are available; development has been retarded by general abundance of good-quality stream waters. Withdrawal for public supplies is about equal to combined withdrawals for industrial, irrigation, and rural-domestic uses. Ground-water resources in many island and peninsular areas are extremely valuable but inadequately appraised.
Limited distribution of large-yield aquifers; excessive dissolved minerals at places, including salty water; deterioration of water quality resulting from disposal of household wastes and water used for air conditioning; declining water levels in basalt aquifers, local waterlogging.	Continued local deterioration of water quality resulting from waste-disposal practices; continued depletion of water in basalt aquifers.	Reduction of pollution from waste disposal; promotion of well designs best suited for improved yields from marginal sedimentary aquifers; additional pumpage from alluvial aquifers; possible use of salty-water aquifers for subsurface storage or disposal of fluids; pumping from waterlogged areas as drainage measure.	Very large additional supplies are available, chiefly from alluvial aquifers, especially those along Columbia River. Industrial and irrigation uses constitute about 90 percent of total ground-water use. Development will be constrained by limited availability of large-yield aquifers, water-quality problems, and declining levels in basalt aquifers.
Lack of adequate information.	Some undesirable dissolved minerals may be present locally.	Forest irrigation in areas of favorable topography and soils; drainage, by artificial tunnels, for hydropower generation; controlled drainage for support of low-level flow or quality of streams.	Ground water is of good to excellent quality and recharge is adequate to support almost any conceivable withdrawals. Development will be severely restricted by remoteness, short growing season, and great depth to water table in many places. May have potential for geothermal development at places.
Water quality, generally not as good as in other major ground-water reservoirs; lack of adequate information; water-logging in some basin-floor areas.	Major problems unlikely until development increases considerably. Intensive pumping for irrigation could easily deplete aquifers that receive little recharge. More waterlogging is likely if some basin-floor areas are irrigated.	Greater development of ground water in most areas; use of deep aquifers for storage or disposal of fluids. Possible development of geothermal ground water.	Young volcanic aquifers are capable of the largest yields to wells, but much of the available ground water is stored in sedimentary rocks. Availability of ground water is limited by great depth to water in many places and meager recharge. Reservoir system is complicated by abundant faulting. Development will be constrained by short growing season, remoteness, by locally poor water quality, and by risks in prospecting for large-yield aquifers owing to inadequate information.
Declining water levels and local depletion of the ground-water reservoir; competition for available supplies; waterlogging.	Continuing and growing areas of water-level decline; some actual depletion of water in aquifers of limited extent and recharge; increased waterlogging caused by increased irrigation.	Additional ground-water withdrawal, especially in deeper aquifers and away from areas of concentrated pumping; greater use of sedimentary aquifers; conjunctive use of surface water and ground water; deep subsurface waste disposal; lining of leaking well bores and improvement of new-well construction; artificial recharge using surplus stream water; salvage of some evapotranspiration discharge; reducing and forestalling waterlogging.	In much of the area the basalt aquifer is the only available source of rural-domestic, stock, and public water supplies. Where recharge is small, the bsalt aquifer is very susceptible to overpumping and depletion because of the large rate of yield and very small storage capacity. The ground-water is generally of good to excellent quality; hardness and dissolved-iron content are greater than desirable at places.
Conflicts between ground-water withdrawals and surface-water rights; waterlogging; lack of adequate information about ground-water availability at places.	More areas of water-level decline; continuing waterlogging; increasing conflicts with surface-water rights; increased occurrences of local pollution of ground water	Withdrawal of water from untapped parts of the ground-water reservoir; conjunctive use of surface water and ground water; artificial recharge with surplus stream water; salvage of some evapotranspiration discharge; reducing and forestalling waterlogging.	The young volcanic rock aquifer of this area is one of the most extensive and productive aquifers in the U.S.; it is considerably more permeable and porous than most basalt of the Columbia Plateau ground-water reservoir, and its storage capacity may be on the order of 20 times greater, volume for volume. Water from the younger volcanic and sedimentary rocks usually has satisfactory quality for most uses. Some of the hottest (90°C) and most mineralized ground water in the region is found in some of the older, less permeable rocks.
Inadequate total supply; conflicts between ground-water uses and surface-water rights; waterlogging; unsatisfactory water quality.	Increased competition for available water supplies; spread of ground-water pollution; salt-water intrusion near the Pacific Ocean.	More beneficial use of the total water supply through conjunctive use and management of both surface water and ground water; reducing and forestalling local pollution and waterlogging; salvage of some evapotranspiration discharge.	The aggregate volume of the reservoir rock materials in areas of this category is several hundred cubic miles. In many places these are the only usable sources of fresh ground water; examples are deposits along the coastlines of the Pacific Ocean and Puget Sound, and stream-valley deposits in widely scattered areas that otherwise are underlain by impermeable rocks. The locations of these smaller areas can be found by comparing figures 7 and 8. They are described in greater detail by Mundorff (CNPTS, 1970b).

5. Comprises areas in southwestern part of Subregion 5, southeastern part of Subregion 7, and all of Subregion 12, of the CNPTS study.
6. Comprises areas in southern part of Subregion 2, eastern part of Subregion 3, western part of Subregion 6, and northern part of Subregion 7, of the CNPTS study.
7. Comprises areas in central and southern parts of Subregion 4, eastern part of Subregion 5, and southern part of Subregion 6, of the CNPTS study.
8. Mainly in Subregions 1, 2, 4, 6, and 10, of the CNPTS study.

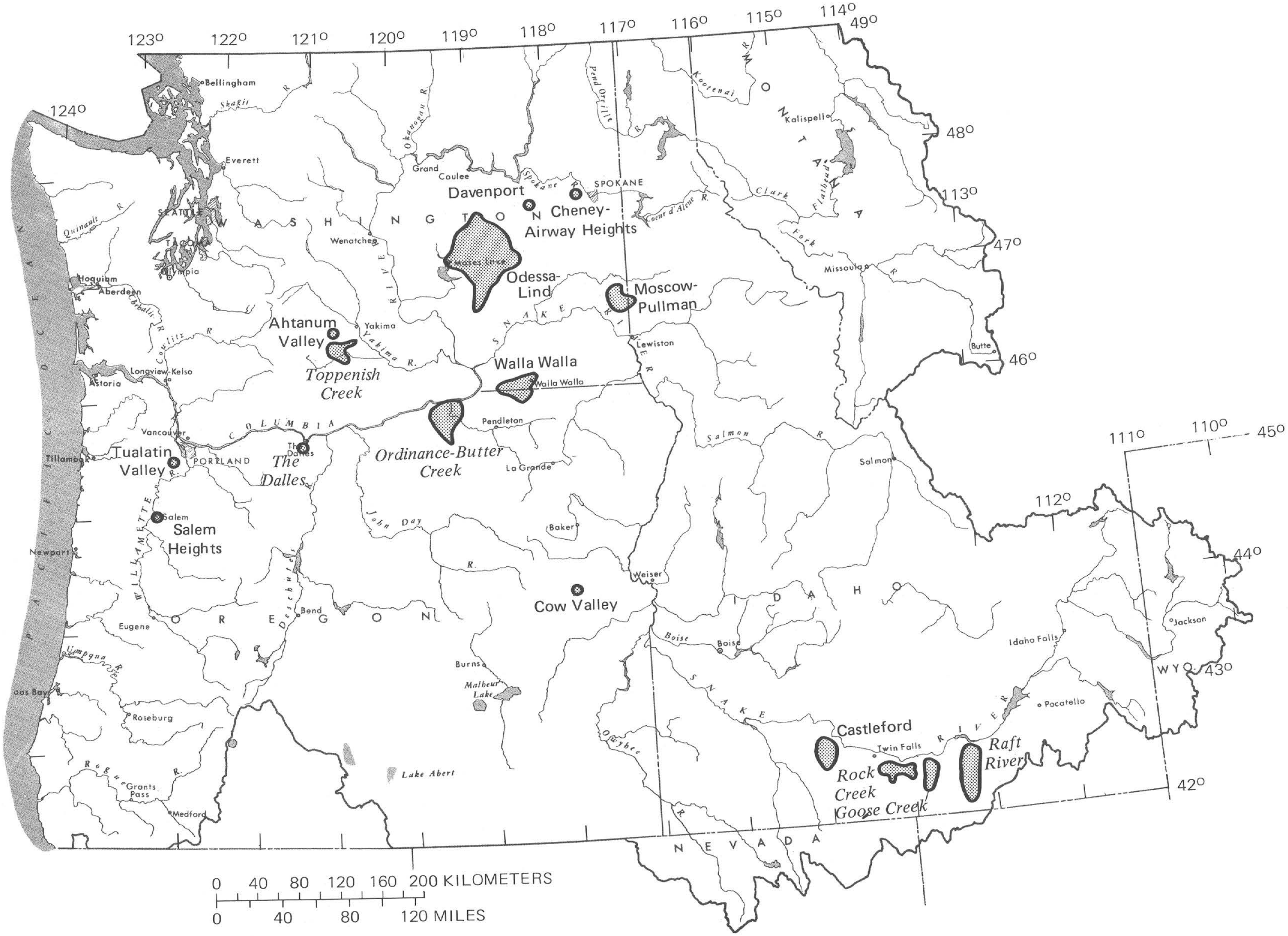


FIGURE 9.—Location of areas where significant declines in ground-water levels have occurred. Rates and duration of decline are listed in table 2. Circles represent areas where extent of decline is indefinite or too small to be shown precisely at this scale.

TABLE 2. *Summary of information about water-level declines*

[Areas shown in figure 9. Values represent net differences between yearly high water levels:]

Area and reference report	Decline	Aquifer(s)	Main use(s) of water	Remarks
Salem Heights (Foxworthy, 1970)	As much as 8 ft/yr, at least 38 ft total by 1961; thereafter, levels have risen gradually.	Basalt (small extent)	Public supply, industrial	Alternative public water supply was provided in 1961; aquifer later used mainly for artificial recharge and supplying peak demands.
Tualatin Valley (Bartholomew and others, 1973)	As much as 12 ft/yr; more than 40 ft total, early 1960's to 1974; thereafter, levels have generally risen.	Basalt	Irrigation, public supply	Declared to be a critical ground-water area by Oregon State Engineer in 1974; that same year, the Wolf Creek Irrigation Project began supplying water from Tualatin River and ground-water use declined.
Cow Valley (Brown and Newcomb, 1962)	As much as about 3 ft/yr by 1959, slower by late 1960's.	Basalt and overlying sand and gravel	Irrigation	Declared to be a critical ground-water area by Oregon State Engineer in 1959; pumpage restricted thereafter.
The Dalles (Bartholomew and others, 1973	As much as about 6 ft/yr by 1965; levels largely stabilized since 1970.	Basalt (faulted and folded)	Irrigation, industrial, public supply	Declared to be a critical ground-water area by Oregon State Engineer in 1959. Substitute water supply from Columbia River was provided by The Dalles Irrigation Project beginning in 1967.
Ordnance-Butter Creek (Bartholomew and others, 1973)	Ranged from less than 4 to about 40 ft/yr, 1961–73.	Basalt and overlying gravel	Irrigation, industrial, public supply	Declared to be a critical ground-water area by Oregon State Engineer in 1976.
Walla Walla (MacNish and others, 1973)	As much as 15 ft/yr; total as much as 150 ft since the late 1890's.	Basalt	Irrigation, industrial, public supply	Rate of decline is expected to slow greatly unless pumpage continues to increase substantially.
Ahtanum Valley (Foxworthy, 1962)	As much as 3½ ft/yr, 1953–57.	Basalt	Irrigation	Additional large-yield wells tapping the basalt have been restricted by Washington Department of Ecology.
Toppenish Creek (U.S. Geol. Survey, 1975)	As much as 7 ft/yr, 1960–70	Basalt	Irrigation	Yakima Tribal Council was considering (1977) prohibiting additional large-yield wells tapping the basalt, and further regulation of pumping.
Odessa-Lind (Luzier and Skrivan, 1975)	As much as 40 ft total, 1967–71.	Basalt	Irrigation	Washington Department of Ecology is trying to regulate pumping so that progressive decline does not exceed about 10 ft/yr.
Davenport (Luzier and Burt, 1974)	Began about 1966; amounted to about 17 ft (3.4 ft/yr) during the period 1972–77.	Basalt	Irrigation	Declines have been monitored, but no regulation of pumping had been imposed by 1977.
Cheney-Airway Heights (Luzier and Burt, 1974)	Generally less than 5 ft/yr.	Basalt (relatively thin)	Irrigation, public supply	The basalt (only aquifer available) is unusually susceptible to total depletion.
Moscow-Pullman (Barker, 1979)	Began in 1890's; total more than 100 ft at places, but averaged only about 1 ft/yr.	Basalt and interbedded sand	Public supply, irrigation	Declines are expected to slow unless future pumping continues to increase.
Raft River Valley (Sisco, 1974)	Began by at least the early 1950's; has been as much as about 5 ft/yr.	Basalt and sedimentary rocks	Irrigation	Idaho State Reclamation Engineer declared the valley to be a critical area in 1963, and restricted the drilling of additional wells; declines subsequently slowed or stopped.
Rock Creek and Goose Creek (Sisco, 1974)	As much as 22 ft/yr (total greater than 200 ft) 1961–72 in limestone aquifer; as much as 5 ft/yr in other aquifers.	Basalt and other volcanic, alluvial, and limestone rocks	Irrigation, industrial	Idaho State Reclamation Engineer stopped issuing well permits in 1962; thereafter, declines slowed or stopped.
Castleford (Sisco, 1974)	Mostly in the range of 2–4 ft/yr; as much as 60 ft total since the 1960's.	Volcanic rocks	Irrigation	Idaho Department of Water Resources closed the area in 1974 to further ground-water development.

WATER-QUALITY PROBLEMS

Water quality is presently not a significant limiting factor to the use of water from the major ground-water reservoirs. Although at places some dissolved constituents are found in concentrations greater than desirable for some purposes, most of the ground water is considered good to excellent for common use. Saline ground water is known to underlie several hundred square miles of the major ground-water reservoirs, but it is generally at considerable depth in areas where other sources of fresh ground water are available. Contamination resulting from man's activities is a growing problem, but only in a few areas has it reached proportions that cause serious limitations to continued use of the ground water.

The data that are presently available on ground-water quality pertain mostly to inorganic chemical constituents of the water that occur in varying amounts under natural conditions. In this respect, the data are mostly indicative of "baseline" conditions. Data on occurrences of organic compounds, which include most pesticides and many industrial products, are gradually becoming increasingly available, but are commonly related only to known or suspected cases of ground-water contamination.

PROBLEMS OF NATURAL ORIGIN

The most significant problems involving natural ground-water quality are:

DISSOLVED IRON

Probably the most widely bothersome natural constituent in the ground water of the region is dissolved iron, sometimes in combination with manganese. It occurs in undesirable concentrations at places in all the major ground-water reservoirs.

Dissolved iron does not affect the usefulness of ground water for irrigation, but causes problems in some industrial uses of the water and in household use where it may impart undesirable taste and color to drinking water and cause staining of plumbing fixtures and laundry. Some type of treatment (usually simple) to remove or reduce the effects of dissolved iron is a common adjunct to the development of ground-water supplies for public or individual domestic uses in the region.

SALINITY

Ground waters containing enough dissolved minerals to be considered "saline" waters probably underlie much of the area of the major groundwater reservoirs but are troublesome in only a few places. Well waters with dissolved-solids concentrations of 1,000 mg/L (milligrams per liter) or more have been found mostly in the Puget Sound, Willamette Valley, High Desert, and Southern Idaho ground-water reservoirs. Ground waters having dissolved-solids concentrations greater than 1,000 mg/L are mainly in older rocks that are not permeable enough to be important aquifers, and almost all these areas also have freshwater aquifers capable of larger yields. The saline ground waters are tapped by wells generally deeper than 100 feet, but in a few coastal areas of the Puget Sound ground-water reservoir, salty water is pumped from shallow wells. Also, saline ground water from older rocks locally migrates into shallow aquifers, and even discharges at the land surface as mineral springs in the High Desert and Southern Idaho ground-water reservoirs. In the latter reservoir area most of the springs that yield water with dissolved-solids concentrations greater than 1,000 mg/L are thermal springs.

Throughout the region, well waters having dissolved solids concentrations of 3,000 mg/L or more are rare, and generally represent seawater intrusion (Puget Sound ground-water reservoir) or thermal ground water (High Desert and Southern Idaho ground-water reservoirs).

OTHER DISSOLVED CONSTITUENTS

In addition to iron, a few other dissolved constituents occur naturally in waters of the major ground-water reservoirs in undesirably high concentrations. These occurrences are generally rather localized, in terms of aquifer zones as well as areal extent, and are mostly in the arid parts of the region. They tend to be near the margins of the major ground-water reservoirs, where the important aquifers are close to older rocks which generally are the sources of the undesirable constituents. These occurrences include concentrations of sodium and boron that are excessive for irrigation waters, mostly at places in the area of the High Desert ground-water reservoir, and concentrations of fluoride that exceed national drinking water standards, mainly at places in the High Desert and the Columbia Plateau ground-water reservoirs and a few places in thermal waters in the Southern Idaho ground-water reservoir (National Academy of Sciences and National Academy of Engineering, 1973).

The only known naturally occurring dissolved constituent in the region posing a health threat to humans is arsenic in ground water that was used for domestic supplies in the southern part of the Willamette Valley ground-water reservoir. However, that threat was recognized (Goldblatt and others, 1963) and alternative supplies developed, and the occurrence is now significant mainly as a historical reminder.

PROBLEMS RELATED TO MAN'S ACTIVITIES

Degradation of ground-water quality as a result of man's activities is a greater problem in this region than the naturally occurring water-quality characteristics, but it has not reached the major proportions found in some other regions. Degradation of the quality is, as would be expected, related largely to population distribution, being best known and most varied in cause where people and industries are concentrated.

CONTAMINATION FROM THE LAND SURFACE

Known and suspected occurrences of ground-water contamination from sources at the land surface are numerous, but so far no major ground-water supplies have been abandoned for this reason. The sources of such contamination differ widely, and include such things as solid-waste landfills, spilled chemicals and petroleum fuels, wastes from mining and milling operations, waste-treatment lagoons, feedlots, large wood-waste disposal sites, and fertilizer and pesticide applications. This type of contamination occurs at places in all the major ground-water reservoirs, except possibly in the High Cascades, and in many of the smaller ground-water reservoirs.

In the more populous areas west of the Cascade Range, solid-waste disposal sites are among the more obvious sources of contaminants. In these areas water from the abundant precipitation enters and percolates through the disposal sites, dissolving and carrying material from the wastes and becoming a generally noxious liquid called "leachate." As with other types of contamination from the land surface, migration of the leachate down to the ground water may take many years, and even covered disposal sites remain as pollution sources for years after their operation is stopped (Wilson, 1975).

Considering the incidences of known and suspected contamination, the relatively small number of apparent problems seems remarkable. The principal reasons seem to be:

1. Public-health officials and others have been alert in recognizing and reacting to some cases of contamination.
2. The soil and shallow rock materials adsorb or filter some contaminants.
3. Dissolved contaminants, moving through the unsaturated soil and the ground water, do not generally disperse widely but rather tend to move along narrow paths that make detection and sampling difficult; thus, some problems have not been recognized or have been underestimated.
4. The contaminants generally enter ground water of good quality which is capable of assimilating and diluting the contaminants to acceptable concentrations.
5. Most contaminants enter shallow aquifers and may discharge into streams without reaching the deeper aquifers that are favored as public water supplies.
6. Rate of movement is so slow that contaminants have not been detected, even at fairly short distances from the sources.

HOUSEHOLD SEPTIC SYSTEMS

Urban and suburban growth, which intensified during the 1940's, 50's, and 60's and which still continues, has involved a pattern of waste disposal that is having a significant impact on ground-water quality. In the developing areas, disposal of household wastes usually was initially through individual septic-tank systems or cesspools, the effluent from which percolated downward toward the ground water. Communal sewer systems and treatment plants normally were installed only where soil conditions prevented acceptable functioning of the individual disposal systems, or after housing densities and attendant waste discharges caused public-health hazards too great to ignore. In the meantime, contaminants from the household wastes have accumulated in the soils and in the upper part of the ground-water system.

Although a proper septic tank system is designed to destroy most or all bacteria in the household wastes, inorganic and some organic compounds pass through the system in the effluent and enter the soil. Where the homes and disposal systems are densely spaced, large concentrations of these compounds have been added to the soil column. Because of the usually slow rates of liquid movement underground, years or even decades may pass before the effluent from the septic tanks in a new housing development shows up as measurable contamination in a well or stream fed by the ground water. However, in this region those years and decades since the most intensive suburban growth are adding up, and increasing concentrations of certain dissolved solids from household sewage can be found in the shallow ground water beneath such areas. Several lakes in the Puget Sound ground-water reservoir area that are fed by shallow ground water have deteriorated for this reason. Also, contamination of the ground water beneath a suburban area east of Portland, Oregon has been reported and attributed to septic-tank effluent (Quan and others, 1974). Studies of ground-water quality have been or are being made in several other areas in anticipation of the problem, including areas southwest of Tacoma, Washington (Lakewood area), east of Spokane, Washington (Spokane Valley), near Boise, Idaho (Boise Valley), and southeast of Kalispell, Montana (Swan-Avon Valley).

SALTWATER INTRUSION

In coastal areas of the region, including areas of the Puget Sound ground-water reservoir and smaller ground-water reservoirs along the coasts of Oregon and Washington, the known intrusions of seawater into freshwater aquifers are surprisingly few. This is largely due to the general abundance of precipitation to recharge the coastal aquifers. Also, the pumping from the smaller coastal ground-water reservoirs has not yet reached major proportions and, in Oregon, few productive aquifers are in contact with seawater.

At present, the aquifers contaminated by modern seawater are probably outnumbered by those contaminated by relict seawater contained in extensive deposits of older marine sedimentary rocks. In the Willamette Valley ground-water reservoir and some smaller ground-water reservoirs west of the Cascade Range, intensive pumping of wells that tap younger aquifers has locally caused migration of salty water from those adjacent older rocks.

PROBLEMS RELATED TO ARTIFICIAL RECHARGE AND DISPOSAL WELLS

In Portland, Oregon, and a few places in the Puget Sound area, ground water, returned underground following its use for heating or cooling, has resulted in local water-quality problems. Not only is the water returned to the aquifers at a drastically different temperature, but, in several places, aeration of the recharge water has promoted the growth of nuisance bacteria which reduce the permeability of the aquifers in the vicinity of the recharge well.

Related problems result from the use of wells for disposal of surplus irrigation water and waterborne wastes from households and other sources. Such disposal is workable only where the aquifer materials are extremely permeable, so that they can assimilate the waste products without rapidly clogging. Disposal wells have been used in the region for many years, mainly in the High Desert and especially in the Southern Idaho ground-water reservoirs. In the latter reservoir there are thousands of disposal wells. According to Whitehead (1974, p. 1) and Seitz, La Sala, and Moreland (1977, p. 2), most of the disposal wells in the eastern part of the Southern Idaho ground-water reservoir are for disposal of household wastes, but most of the water injected is from irrigation tail water and street runoff. The widespread use of disposal wells is considered to be clearly a potential threat to the quality of water in the major basalt aquifer which is the source of almost all the water used locally for household and community supplies. Experiments reported by Graham, Clapp, and Putkey (1977) suggest that some bacteria introduced through disposal wells may survive for a month or more after disposal stops. There is some local concern that the waste water may increase the nutrient content of the ground water that discharges into the Snake River and into lakes and ponds in canyon-bottom lands and contribute to occasional algal blooms in those waters.

WATERLOGGING

Waterlogging, the buildup of ground water to such a shallow depth that it hampers the use or productivity of agricultural land, occurs in all the major ground-water reservoir areas except the High Cascades, and in areas of many of the smaller ground-water reservoirs, as well. The region reportedly had about 2.5 million acres of "wet cropland" in 1966 (CNPTS, 1971b, p. 17).

In the more humid parts of the region, especially west of the Cascade Range, waterlogging is mainly a naturally occurring condition. It is most troublesome in low-lying, typically floodplain areas where the water table is never far below the land surface. Planting and crop production are delayed because the water table rises as a result of seasonally abundant precipitation, flooding of through-flowing streams, or runoff from adjacent lands, and the soil drains slowly.

In the drier parts of the region, the problems of waterlogging are characteristically found in flat or gently sloping areas that are irrigated with diverted stream water. In some places, the saturated zone that extends to the land surface and waterlogs the soil is temporarily perched above the general water table by a relatively impermeable material (for example clay, cemented gravel, or the top of the basalt). In many places, however, the application of irrigation water has raised the general water table to near the land surface, so that all the soil and underlying rock materials are saturated. The areas most susceptible to waterlogging by ground water are the localities of natural discharge of upwelling ground water—low-lying floodplains and the lowermost parts of closed basins or faultbounded ground-water "compartments." Some of these areas of ground-water discharge were waterlogged under natural, preirrigation conditions, but irrigation extended and worsened the waterlogging. Most, if not all, of the major irrigation projects have had associated waterlogging problems. In the Columbia Basin Irrigation Project of central Washington, for example, the seepage from canals distributing the Columbia River water and the application of the water for irrigation have caused the water table to rise more than 100 feet at places, waterlogging a few thousand acres of land.

INADEQUATE INFORMATION

Inadequate information about the ground-water reservoirs and their role in the total water resources of the region presently restricts the ability to deal effectively with the known and foreseeable problems, and hampers future management opportunities. There are two main levels of information needs: One is for the public officials, consultants, and others having major responsibilities in planning for, developing, regulating, or conserving the water resources; the second is for the direct user of the water resource—the irrigator, plant manager, water superintendent, and the general public. The two information levels largely overlap, but not entirely. The following discussion pertains mainly to the first level, and includes needs for new basic information about aquifers and their potential, needs for more quantitative information, and needs for water-quality information.

Probably no truly unknown additional major freshwater aquifers exist in the region, but the knowledge about every aquifer is incomplete, and for some aquifers is very sketchy, particularly in the more arid, sparsely inhabited parts of Idaho, Oregon, and Nevada. Geologic mapping in many of those areas has been of a reconnaissance type; consequently, although the general character of the aquifers is known, their actual potential can only be inferred. Because these areas are mostly in arid parts of the region, lack of firm water supplies is a severe and obvious deterrent to most types of development. Occasional private prospecting efforts to develop ground-water supplies in these areas during the 1960's and 1970's have been farily successful, although often unduly expensive. Much greater and more productive use of some of these areas could be expected if definitive information about ground-water potential were available. Information about potential aquifers in the deeper parts of some of the major groundwater reservoirs and on ground-water availability in some of the coastal areas of the region is also lacking. Until the ground-water conditions, including the geologic controls on the occurrence and movement of ground water, have been studied in greater detail, development of additional supplies of ground water will be largely a prospecting venture, with associated risks and expense.

For many of the ground-water reservoir areas, information is available about the general occurrence of the ground water and character of the aquifers, but water-management needs call for more quantitative data. Such data needs are likely to include volumes of a ground-water reservoir and of water it contains, amounts of pumpage and resultant water-level change, and numerical values for hydraulic characteristics of the aquifers. Quantitative data are considerably more difficult and expensive to obtain than more general information, commonly requiring the drilling of wells, the complex testing of aquifers, and the metering of discharges of large-yield wells. However, there is no substitute for the quantitative information in some types of water-management procedures, such as the use of mathematical models to predict future changes in the ground-water reservoirs (see section on "Management using Predictive Models").

A type of information that is increasingly needed, especially in the developing areas, is information on the quality of the ground water. More information is needed about the inorganic chemical constituents (the kinds of data that now are available for many ground waters), especially for previously unexplored aquifers and those susceptible to contamination. In addition, programs of reliable sampling and analysis for noxious organic compounds are needed at many places where such compounds present a threat to valuable ground-water sources—for example, in some areas of pesticide application, industrial waste disposal, and chemical spills.

COMPETITION FOR AVAILABLE SUPPLIES

Of the major ground-water reservoirs, the competition for available water supplies is a serious problem only with respect to the Columbia Plateau and the Southern Idaho ground-water reservoirs. It is also a major regional problem because: (1) It also occurs in areas of several smaller ground-water reservoirs; (2) it involves most, if not all, the States comprising the region, (3) the amount of water involved in the competition is large, and (4) the problem is critical to prospects for fullest and most effective use of the total water resource.

In the area of Columbia Plateau ground-water reservoir, the competition for available supplies has produced problems of interference between pumping wells, conflicts between ground-water and surface-water rights, and litigation between Indian and non-Indian users of ground water and surface water. The early, uncontrolled development of limited ground-water supplies caused rapidly declining ground-water levels that led to pumping restrictions in areas listed in table 2.

In the area of the Southern Idaho ground-water reservoir, surface and ground water are closely related at many places. Development of large supplies of ground water in the eastern part of the area affects to some degree return flows to the Snake River farther west;

this interrelationship is also true in some of the basins flanking the Snake River Plain. Therefore, large withdrawals of ground water may have an adverse affect on the surface-water supply, and are, or will be, in conflict with surface-water rights.

ANTICIPATED OR POTENTIAL PROBLEMS

Problems foreseeable in the future for the Puget Sound ground-water reservoir include local deterioration of water quality as a result of waste-disposal practices, and seawater intrusion associated with additional pumping in near-shore areas. The growth of these two problems seems to be an inevitable consequence of present waste-disposal practices and developmental trends in near-shore areas. Some of the better aquifers in this part of the region lie beneath areas that have fairly dense spacing of household septic-tank disposal systems. Doubtless the combination of abundant recharge to dilute the wastes and the slow movement of water underground has helped limit the effects of potential pollution from these waste-disposal systems. However, pollutants now in the soil and shallow rock materials will continue to migrate downward to the ground-water and increasing effects of these pollution sources can be expected in the future despite whatever near-term management steps are likely to be taken. Local problems of seawater intrusion are also a likely future consequence of indiscriminate development of ground water in near-shore areas. This problem may be troublesome at places but will be somewhat self-limiting; pumping that induces landward movement of the salty water generally decreases as the wells "go salty."

For the Willamette Valley ground-water reservoir, foreseeable problems include further depletion of water in the basalt aquifers and water-quality deterioration in areas of waste disposal by landfills and by densely spaced septic-tank systems.

No special problems are foreseen in greater development of the ground-water of the High Cascades ground-water reservoir. Meager water-quality information indicates that the ground water is of good to excellent quality, but experience in similar terranes suggests that undesirable dissolved minerals might be present locally. The available recharge is adequate to support almost any conceivable direct withdrawals of ground water with little impact on the low-level flows of the streams that drain these aquifers. The short growing season and the remoteness of the areas underlain by this reservoir suggest little possibility that much of this supply will be needed within the mountains in the near future, and most of the reservoir probably will remain an untapped reserve for many years.

Future problems in the area of the High Desert ground-water reservoir are likely to be largely the same as present problems—namely, limitations on ground-water supplies imposed by meager recharge, locally poor water quality, and waterlogging. In addition, areas of intensive pumping may develop or enlarge, and result in significant water-level declines, perhaps to the extent of long-term depletion of the ground water in localized areas (table 1). Future major ground-water development may tend to be areally concentrated for two reasons: (1) A relatively small amount of land in the area is privately owned, and (2) successful wells tend to foster prospecting for ground water in their immediate vicinity. Management of the ground-water reservoir, however, is not likely to be a major problem until development proceeds to a considerably greater extent than at present.

In the future, problems related to ground water in the Columbia Plateau ground-water area are likely to be of the same kinds as at present (table 1) but more extensive and in new places. Problems of declining water levels are expected to become more widespread as development of water from the basalt progresses. Because the basalt has relatively small storage capacity, any intensive withdrawals from wells tapping the basalt can be expected to cause sizable water-level declines. Examples of areas now undergoing such development, where the increased pumping from the basalt is likely to cause significant water-level declines within a few years, are the Moxee Valley and Horse Heaven Hills areas (not shown on included maps) both in south-central Washington, respectively east and southeast of Yakima (fig. 7). In areas of presently declining levels, the declines are likely to continue until limited by such factors as excessive pumping lifts, importation of surface-water supplies (as in The Dalles area, Oregon, table 2), legal restriction on pumping withdrawal, or actual dewatering of the available aquifers—a possibility in the Cheney-Airway Heights area, eastern Washington (table 2; also Luzier and Burt, 1974, p. 47). Where the depleted zones include shallow aquifers which supply most of the rural domestic and stock water and the dry-season flow of small streams, troublesome reductions may occur in the streamflow and in these rural well-water supplies. In areas having many wells that penetrate deeply into the aquifer system and are open to more than one aquifer zone, the continual leakage from one zone to another through the well bores may contribute to declines in some aquifer zones.

Future ground-water problems in the Southern Idaho ground-water reservoir area probably will be related mainly to further declining water levels (local overdrafts on the ground-water reservoir), increasing conflicts with surface-water rights, spreading of water-logging associated with the growth of irrigated farming, and increasing contamination. If withdrawals for irrigation follow the predicted increasing trend, declining ground-water levels can be expected to show up in new places and perhaps resume in some of the areas already noted (table 2). The decrease of ground water in storage, reflected by water-level declines, is likely to affect the low flow of streams and, therefore, the availability of surface water for use under existing rights. The greatest undesirable impacts on surface-water rights likely would result from development of additional large supplies of ground water in the eastern and northern parts of the reservoir system.

Soluble residues and waste products from intensive agriculture and processing of agricultural products are expected to be sources of increasing ground-water contamination. Most organic compounds tend to be filtered out or adsorbed in their passage through the first few feet of soil; however, dissolved salts, including the major constituents of fertilizers and some pesticides, infiltrate the soil and percolate downward readily with the rainwater and irrigation water. Some of the best evidence for this type of ground-water-quality deterioration is in the extensive Columbia Basin Irrigation Project (Columbia Plateau ground-water reservoir; Van Denburgh and Santos, 1965), but the effects are being felt and can be expected to increase also in the Southern Idaho ground-water reservoir and elsewhere in the more arid parts of the region.

The major water-related problems that are foreseen for the areas of the smaller ground-water reservoirs are increasing conflicts in the use of surface water and ground water and increasing water-quality problems.

Some of the smaller ground-water reservoirs, such as isolated coastal sand deposits or valley-filling alluvial deposits in areas of impermeable bedrock, are extremely valuable as sources of water but, because of their relatively small volume, have limited waste-assimilating capability. The preservation of good-quality ground water under conditions of expected growth in these reservoir areas will require some difficult (and probably expensive) choices regarding waste-disposal practices and land use. An example is in the Spokane Valley-Rathdrum Prairie area, Washington-Idaho, east and northeast of Spokane (fig. 7; Drost and Sites, 1978). Because of the importance of the ground-water reservoir in that area as a source of public water supplies and the lack of suitable alternative supplies, the U.S. Environmental Protection Agency, in 1978, designated the reservoir as a "sole-source aquifer" (U.S. Environmental Protection Agency, 1978). Such a designation restricts future waste-disposal practices and land uses that might degrade the ground water in that area.

By 1977, the intrusion of sea water in the western part of the region was not a widespread problem. However, despite strong trends to protect these shorelands through State and Federal legislation, the projected development in these areas doubtless will lead to intensified local ground-water withdrawal that will be accompanied by problems of potential seawater intrusion. Elsewhere in the region, the induced migration of saline water into the freshwater aquifers of the small ground-water reservoirs is not expected to be significant unless pumping is intensive in areas adjacent to older saline-water-bearing rocks. Saline-water problems also may accompany future development of geothermal energy in the smaller reservoir areas.

MANAGEMENT OPPORTUNITIES AND CONSTRAINTS

Management opportunities presented by ground-water reservoirs in the region are discussed below, along with related constraints and problems. As in foregoing discussions, the major ground-water reservoirs are emphasized, but most of these management opportunities and constraints apply also to the smaller ground-water reservoirs.

DEVELOPMENT OF ADDITIONAL SUPPLIES

Additional large supplies of water can be developed from each of the major ground-water reservoirs, but most of the reservoir areas have their own set of constraints on such further development. Additional major supplies, large enough for industrial, irrigation, and municipal uses, are available from presently utilized aquifers at places in all the major reservoir areas, but especially in parts of the Puget Sound and Willamette Valley ground-water reservoirs.

In the Puget Sound area, underutilized glacial and alluvial aquifers are capable of meeting much of the foreseeable increase in water demand, such as additional supplemental irrigation water and new industrial and community supplies. Some coastal aquifers contain a considerable resource of fresh ground water that is now flowing to the sea without being used beneficially; however, the optimum use of this resource will require improved information about the coastal aquifers and adroit management to minimize problems of seawater intrusion.

In the Willamette Valley ground-water reservoir, large additional supplies of ground water also are available, chiefly from the alluvial deposits. Not only is the present withdrawal only a small fraction of the natural recharge, but recharge might locally be increased by increasing withdrawals. That is, if more storage space were provided in the aquifer by intensified pumping during the summer months, that space would be largely refilled by abundant recharge water during winter and spring. Also, for many of the large-yield wells near the Columbia River and other major streams, much of the water they produce is induced infiltration from the rivers. That induced infiltration could be increased—at the expense of river flow, if course. Along favorable reaches of the Columbia River, for example, yields of about 50–100 million gallons per day might be obtained per mile of river length (Mundorff, 1964, p. 93).

At places near the margins of the Columbia Plateau and Southern Idaho ground-water reservoirs, large bodies of saturated older sedimentary rock materials occur beneath, overlying, or interfingered with basalt aquifers. These sedimentary rocks can be used more extensively as sources of ground water not only by tapping them directly with effective wells (see section on "Improved Design and Construction of Wells"), but also by inducing these reservoir rocks to drain into adjacent, more permeable basalt aquifers. Such drainage might be accomplished by purposely causing large water-level declines in the adjacent basalt aquifers to accelerate the migration of water from the sedimentary materials.

Where ground-water reservoirs are already heavily stressed by pumping, greatly increased pumping from the same aquifers will tend to increase or create problems of declining water levels and conflicts between water users. It can also accelerate the spread of any ground-water contaminants by increasing rates of ground-water flow in the heavily pumped parts of the ground-water reservoir.

In some areas, increased pumping from presently utilized aquifers probably will include pumping to reduce waterlogging (see section on "Reduction of Waterlogging") and to salvage ground water now used by vegetation. Common water-loving vegetation, phreatophytes and hydrophytes, do not grow extensively in the region, but they are abundant enough in the lowlands and along stream courses to consume a significant part of the summer water supply. In the ground-water reservoir areas east of the Cascade Range, where evapotranspiration rates are high and summertime water supplies are especially valuable, some of this water may be economically salvageable. Phreatophytes may be removed by uprooting, mowing, or spraying with growth-retardant chemicals. An alternative, and generally more effective, method of reducing evapotranspiration is to remove the water supply by draining marshes or pumping wells to lower the water table below the root zone.

Destroying the natural vegetation in order to increase the water yield, however, would eliminate possible benefits of the vegetation and might create other problems. For example, the plants may be a valuable habitat for wildlife and shelter for livestock. Moreover, they may inhibit evaporation losses from surface water by shading the water and thereby reducing its temperature. Also, removing all the natural vegetation might create problems of increased flood damage and erosion.

DEEPER AQUIFERS OF KNOWN POTENTIAL

In some of the major ground-water reservoirs, productive aquifers are known to occur at depths greater than the presently utilized aquifers, and thus are in the category of proven reserves. This is especially true for parts of the Puget Sound, Columbia Plateau, and Southern Idaho ground-water reservoirs. Constraints on development of these deeper aquifers include high costs of drilling the required deep wells, less desirable water quality (at places in the Puget Sound and Southern Idaho areas), high pumping lifts, and present availability of more accessible alternative water supplies. The temperature of the ground water increases with depth, and the higher temperature is generally considered to be a constraint to the use of the water for municipal supplies, some industrial purposes and, if sufficiently high, for irrigation.

Three points regarding the future development of deep aquifers in the region should be emphasized. First, in many of the reservoir areas, the total depth of productive aquifer materials, being controlled by the geology, is fairly well known. In these areas, hydrologists can say with some assurance that highly productive aquifers do not occur at greater depths. Second, the productivity of sedimentary aquifers especially, and volcanic aquifers to a lesser extent, locally tends to decrease with greater depth. Third, the withdrawal of water from deeper zones in a presently utilized ground-water reservoir does not necessarily constitute "new" water; although it may increase the short-term supply, in the long term it must be counted as part of the total draft on the reservoir.

NEW SOURCES OF SUPPLY

All the major and many of the smaller ground-water reservoirs offer opportunities for finding and developing water supplies from presently unknown or unproven aquifer zones. This is especially true of the sparsely inhabited areas, including much of the High Cascades and High Desert, and parts of the Columbia Plateau and Southern Idaho ground-water reservoirs. Much of this sparsely populated land has low foreseeable demands for ground water because of high altitude or rugged terrain, short growing season, scarcity of arable land or privately owned land, and adequacy of surface water (at places). A further constraint on ground water development in unproven areas will be the high cost and financial risk of prospecting for new sources of supply. Also, especially in the High Desert area and in deeper zones elsewhere, undesirable water quality may be a constraint. Demands for ground water doubtless will increase somewhat as additional information about the potential reservoirs becomes available, and as new uses develop such as forest irrigation, fish-hatchery supply, and energy production (see section on "Geothermal Energy"). Also, in some remote areas where streams are contiguous to permeable aquifers with a large storage capacity, ground-water supplies might be economically developed to supplement the low flow of the stream during relatively short but intense periods of drought.

CONTAMINATION ABATEMENT AND AVOIDANCE

Significant opportunities exist for reducing presently occurring contamination of ground water and for avoiding future contamination in critical areas of ground-water need. These opportunities exist mainly in the Puget Sound, Willamette Valley, Columbia Plateau, and Southern Idaho ground-water reservoirs, and several smaller reservoir areas.

Effective abatement of presently occurring contamination must start with identification of the areas undergoing the contamination and determination of the sources and degree of contamination before appropriate regulatory or management steps are formulated and undertaken. A number of areas of ground-water contamination in the region—mainly areas of solid-waste disposal, concentrated septic-tank systems, disposal wells, and chemical spills—have been or are being studied to some degree, and some monitoring of ground-water quality in impacted areas has been going on for decades. However, few of these studies have yielded information that is adequate for such purposes as deciding between alternative abatement schemes or estimating future die-away rates of contamination following abatement. For such purposes data are needed, for example, on: Rates and modes of contaminant movement in the ground-water system and the unsaturated zone above the ground water; adsorption of the contaminants on the soil and rock materials; and the ultimate discharge of the contaminants from the ground-water system. Much of this information must be obtained through test drilling and detailed subsurface sampling.

Actual abatement steps might include stopping a specific waste-disposal operation, changing the locality or method of waste disposal, clean-up of accidental spills, pumping or artificial recharge to change flow directions of the contaminated ground water, or even the direct pumping of the contaminated water for disposal elsewhere. In the humid parts of the region west of the Cascade Range, the only practical way to reduce contamination from landfill disposal may be to collect as much as possible of the leachate and other drainage from the disposal sites and treat these waste waters to make them acceptable for redisposal by dilution in large streams or marine waters.

Avoidance of future ground-water contamination should focus on the parts of the ground-water reservoirs that are most important to protect and retain in a high-quality state, such as aquifers that are sources of present or anticipated public supplies, aquifers that are the only feasible source of water supply, or those clearly advantageous economically or otherwise as present or future high-quality supplies. For example, ground-water resources are extremely important in marine island and peninsular areas where sites for surface reservoirs are limited, stream supplies are inadequate or subject to pollution, and where great costs would be incurred in piping water from dependable mainland sources.

Because of the importance of considering future needs in decisions about protection of the ground water, such decisions are best made within the framework of comprehensive land-use and water-use plans. After a decision that a particular ground-water body should be protected, the steps necessary to avoid ground-water contamination must be taken by the agency having jurisdiction over use of the overlying land or recharge areas. Depending on the ownership and jurisdiction of the land, the protective measures may include: Land zoning to control population density; prohibition of waste disposal; open-space designation of identified recharge areas, or "watershed" designation with accompanying restriction on entry into recharge areas. Also, because withdrawal of ground water can accelerate the spread of contaminants, the protective measures might include restrictions on pumping wells in areas subject to salt-water contamination.

In many areas where contaminants are being added to the subsurface, remedial action apparently will not be started before there is obvious evidence that significant contamination of valuable ground-water supplies has occurred. Future impacts of the contamination might be lessened in those areas if the onset of the contamination can be detected as soon as possible. This will require identification of such areas (if they have not been identified already), studies to determine the degree or threat of the contamination and the subsurface conditions in the threatened areas, and monitoring programs to detect the onset and trace the movement of contamination. In most cases, existing wells will not suffice for an effective monitoring program—special test-observation wells probably will be needed also to provide information not available from supply wells. The monitoring programs in such areas may be needed for decades into the future.

Careful monitoring of the underground disposal of potentially hazardous contaminants—for example, the radioactive wastes in the Hanford, Washington (Columbia Plateau ground-water reservoir) and the Arco, Idaho (Southern Idaho ground-water reservoir) areas—are required by existing environmental protection laws.

IMPROVED DESIGN AND CONSTRUCTION OF WELLS

Well-construction practices in this region can be substantially improved to the advantage of future development and management of the ground-water reservoirs. Many wells that presently yield less than enough for irrigation, industrial, or public supplies could be brought up to that range through better well construction. In general, the finer the saturated material, the more the yield of the well depends on good design and construction.

Techniques that have been used to increase well efficiency and productivity, and that hold promise for wider application in the region, include:

(1). Recently developed rock-drilling methods and equipment;

(2). use of well screens and graded gravel or sand "packs" for greatest yields from sedimentary aquifers;

(3). use of special drilling fluids that reduce clogging of aquifer pores;

(4). greater use of well-development techniques (surging, chemical treatment, water jets, and so forth) in completion of wells; use of these techniques for wells tapping volcanic, as well as sedimentary, aquifers.

Although some of these techniques are applicable mainly to new well construction, several can be used beneficially on wells that are being rehabilitated or deepened.

One conspicuous opportunity for improvement is the reduction of unwanted vertical ground-water leakage because of "short circuiting" through unlined or leaky well bores (see section on "The Productive Aquifers"). The best way to prevent this cross-bed leakage is to design and construct wells using well casing cemented to the rock materials so as to isolate the different aquifer zones; the casing should be open only to the zone or zones actually to be developed. Installation of casing in existing unlined wells is likely to be much more troublesome, but may be necessary at places in order to reduce ground-water contamination (Foxworthy, 1970, p. 14) or alleviate the draining of aquifer zones tapped for domestic supplies (Luzier and Burt, 1974, p. 44).

The recognition of deficiencies in many of the older wells has led the State water-management agencies in the region to formulate and recommend, and in some cases legally require, minimum standards for water-well design and construction. Moreover, in some areas of intensive ground-water management, such as the Odessa-Lind area of Washington, certain well designs (specified depths of well casing) are made a condition for approval of additional wells. As problems of water-level declines and ground-water contamination increase in the region, the imposition of well-design requirements by State and local water-management agencies is likely to increase.

REDUCTION OF WATERLOGGING

Waterlogging might be reduced by greater pumping from aquifers in some waterlogged areas, and gravity drains within the saturated zone also can be useful; at other places, a reduction in the application of irrigation water may be the only practical corrective measure. At some places a combination of these measures may be the most effective. Pumping from wells to reduce waterlogging is effective only if: (1) Aquifers of at least moderate permeability can be tapped at relatively shallow depths, and (2) the pumping can induce substantial downward migration of water from the waterlogged zone or can intercept significant amounts of naturally upwelling ground water. Moreover, for such remedial pumping to be economically feasible in most cases, there must be beneficial uses for the water pumped from the shallow aquifers. "Relief wells" and drainage tunnels to reduce waterlogging have been used in the area of the Southern Idaho ground-water reservoir for several decades, and relief wells, alone or combined with drains, have been suggested for a waterlogged area south of Yakima, Wash. (fig. 7; Mundorff and others, 1977, p. 81).

The widespread buildup of ground-water levels and occurrences of waterlogging in areas of major irrigation projects strongly suggest that future irrigation projects should be designed, if possible, for importation of only part of the water supply needed, with the balance of the supply to be obtained from aquifers recharged by the irrigation. This approach would not only reduce the amount of surface-water diversion required but would also tend to reduce waterlogging problems.

SUBSURFACE STORAGE

Underground space has been used in the region for some common and some uncommon types of waste disposal. It has also been used to store freshwater and natural gas. The following are brief discussions of the opportunities for and experiences in use of the underground space for these and other types of subsurface storage.

ARTIFICIAL RECHARGE

Artificial recharge—the addition of water to the ground-water reservoir as a result of man's activities—is important to the concept of total water-resources management. It offers possibilities of manipulating input to the ground-water reservoirs in addition to the manipulation of withdrawals that is afforded by regulation of pumping. In the broadest sense, artificial recharge includes not only planned replenishment but also additions to the ground water that are incidental to other activities; it includes not only good-quality water but also the waste water that is added.

In this sense, the most significant type of artificial recharge in the region is that occurring as a result of irrigation. Seepage from irrigated lands and conveyance ditches occurs in all areas where irrigation is extensive, but it is most significant in the more arid parts of the region. Irrigation is the major form of recharge in parts of the Columbia Plateau and Southern Idaho ground-water reservoirs and in some smaller ground-water reservoirs. Recharge from this source is so great at places that waterlogging has become a problem (see section on "Waterlogging").

A related type of artificial recharge is surface spreading, which consists of diverting water from a stream and allowing it to flow over or stand upon permeable material so that it may infiltrate to the ground-water body. Spreading can be accomplished by simply flooding flat areas in which the water can be retained for substantial periods of time, by holding the water in artificially constructed basins or in natural ponds, or by directing the recharge water into ditches or furrows. Surface spreading was used with reasonable success to augment natural recharge for an alluvial aquifer tapped by municipal wells at Richland, Wash. (Price and others, 1965, p. C5–C19), and occurs incidental to the operation of storm-water retention basins in the area of the Puget Sound ground-water reservoir and other urban areas in the region.

A method of increasing the recharge to aquifers, at the expense of flow in contiguous streams, is the deliberate drawdown of ground-water levels in shallow aquifers adjacent to streams so as to induce or increase infiltration of water from the streams into the aquifers (see section on "Development of Additional Supplies"). This practice, called induced infiltration, is fairly common, and is used largely to obtain water for municipal and industrial supplies that requires less treatment than if they were taken directly from the streams. The gain in well supplies by this method, of course, is offset by a corresponding reduction in the flow of the affected streams. However, at places where the wells can be located sufficiently far from the affected streams, the reduction in streamflow caused by the seasonal pumping from wells may be delayed until after periods of low streamflow. This method offers important opportunities for increasing the amount of water available during periods of low streamflow by utilizing even relatively small ground-water reservoirs. Moreover, it is a key to practical conjunctive use of surface and ground-water resources (see section on "Conjunctive Use of Ground Water and Surface Water).

In addition to the disposal of storm-runoff and waste waters through wells (see section on "Problems Related to Artificial Recharge and Disposal Wells"), which is most significant in the areas of highly permeable young basalt rocks (Southern Idaho and High Desert reservoirs), injection of good-quality water through wells for later recovery from the aquifers has been attempted elsewhere in the region. Experiments and trial injection through wells, mainly in the Willamette Valley and Columbia Plateau ground-water reservoir areas, have utilized aquifers of moderate to high permeability, though not as permeable nor nearly as porous as the young basalt. These experiments had limited success. They indicated that the artificial recharge through wells generally is technically feasible, but it requires sediment-free water of good chemical quality, careful injection techniques, and occasional cleaning of the injection well for practical long-term success (Foxworthy and Bryant, 1967; Price and others, 1965). Also, not all the water recharged artificially was recoverable for later use.

Artificial recharge, to be a feasible water-management aid, requires three basic conditions: (1) The aquifer must be at least moderately permeable and must have adequate storage capacity to receive the water; (2) the supply of recharge water must be of adequate quantity and suitable quality; and (3) the water must be economically recoverable from the ground-water reservoir and of a quality suitable for the intended use. Economic considerations may be as complex as the technical aspects in judging the feasibility of artificial recharge. They include consideration of the economic benefits of sustaining or improving the ground water, cost of the artificial recharge operations, value of the water added to the aquifers, and relative value of the recharge water if used for other purposes, such as hydropower generation.

Conditions favorable for artificial recharge probably can be found in several parts of the region, including some of the smaller ground-water reservoirs. In many valleys and basins, there are terraces underlain by young sedimentary rocks which could be potentially productive aquifers except that they are mostly above the normal water table. The water-yielding capability of these terrace deposits depends not only on the character of the rock materials, but also on their saturated thickness. At some places the terrace deposits were unsaturated under natural conditions but have become partly saturated from irrigation water. At other places, the unsaturated deposits await only the artificial addition of water to become valuable storage reservoirs.

Artificial recharge seems to be a strong possibility for increasing the usable supplies of ground water in the Southern Idaho ground-water reservoir. No planned artificial recharge is being done in the reservoir area; however, recharge incidental to irrigation is a major factor in the hydrologic regimen. Mundorff (1962), in his study of the feasibility of artificial recharge of aquifers underlying the Snake River Plain, concluded that surplus water for recharging was available and that artificial recharge was hydrologically feasible. There are several places where water could be diverted to flow by gravity to recharge sites on the Snake River Plain. Opportunities also exist for artificial recharge in basins flanking the Snake River Plain. In some areas, surplus river water is available locally to recharge the aquifers; in other areas no local surplus water is available and recharge water would need to be diverted from one of the major rivers.

Several parts of the Columbia Basin ground-water reservoir area are included in plans for additional irrigation with surface water. These include the East High division of the Columbia Basin Irrigation Project, east-central Washington, and lands adjacent to the Columbia River in south-central Washington and north-central Oregon. These or similar expansions of irrigation using surface water are likely to provide artificial recharge to aquifers underlying the irrigated areas, thereby improving the productivity and dependability of such aquifers. In addition, opportunities may exist for more deliberate artificial recharge using irrigation canals to convey surplus water to recharge sites during the nonirrigation seasons (Garrett and Londquist, 1972, p. 15, 16).

WASTES

Many types of wastes have been committed to subsurface disposal in the region. They range from the least troublesome types, such as burials of nondegrading construction materials, to wastes that are toxic or otherwise dangerous, including the radioactive wastes disposed of at sites near the Hanford nuclear facility, Washington and INEL (the Idaho National Engineering Laboratory), Idaho.

In general, the more hazardous the waste, the farther away it should be from the realm of living things (biosphere); this often requires disposal deep underground. Successful disposal of wastes in underground space with the least undesirable consequences requires thorough knowledge of the geologic framework and of the path that the ground water—and any contaminants derived from the wastes—takes through that framework. Obviously, the more hazardous the waste, the more important this knowledge. Exhaustive studies and elaborate test drilling have been conducted and are being continued in the vicinity of the Hanford nuclear facility, to determine the feasibility of storing high-level hazardous wastes deep in volcanic rocks. At INEL, also, many observation wells have been drilled to monitor the movement of radioactive wastes.

Some rocks, but not all, are worthy of consideration for subsurface disposal of hazardous wastes in areas of the major ground-water reservoirs. Included are deep-lying, older sedimentary rocks containing salty water in the Puget Sound and Willamette Valley ground-water reservoirs, and deep zones of the basalt or underlying rocks in the Columbia Plateau and Southern Idaho ground-water reservoirs. In addition, parts of the High Desert ground-water reservoir seem to offer possibilities. This ground-water reservoir includes a number of closed basins that have no surface outflow and probably insignificant ground-water outflow; there the discharge of water is nearly all by evapotranspiration or from wells. Owing to the remoteness and lack of substantial outflow from much of the area, opportunity may exist for storage of wastes in deep saline aquifers, but additional subsurface studies are needed for verification.

NATURAL GAS

Deep, confined salty-water aquifers in the Puget Sound and Willamette Valley ground-water reservoirs may offer unusual opportunities for underground storage of natural gas in proximity to major urban centers. Confined zones at depths of about 1,800 to 2,100 feet have been used for the storage of many billions of cubic feet of natural gas in a small area a few miles south of the Puget Sound ground-water reservoir. The further use of deep confined aquifers for storage of this type should be based on greatly increased knowledge about subsurface conditions in the areas involved, including deep circulation patterns of the ground water.

IMPROVED MANAGEMENT AND CONSERVATION

Many opportunities exist for improved management and conservation of proven, available water resources. These include greater conjunctive use of ground water and surface water, conservation of existing resources through changes in conveyance and use, and management of water resources with the aid of predictive models of ground-water flow systems. Of these, greater conjunctive use of ground water and surface water probably offer the largest benefits, but this management opportunity also has the greatest problems and constraints.

CONJUNCTIVE USE OF GROUND WATER AND SURFACE WATER

The integral relationship between ground water and surface water is most apparent in the smaller ground-water reservoirs, where the best aquifers commonly are well connected hydraulically to the local stream system. Because of this degree of interconnection, and because the ground-water reservoirs feed the streams through most of the year, any change that has a major effect on the ground water, such as intensive pumping or changes in recharge, generally has a rapid and obvious effect on the streams. The same interrelationship also exists for the larger ground-water reservoirs, creating conflicts between use of wells and stream water (see section on "Deeper Aquifers of Known Potential"), and dooming to failure any attempt to manage effectively either the ground water or surface water separately. Water flowing through an area commonly passes back and forth between the aquifers and the stream channels. For example, in the area of the Southern Idaho ground-water reservoir, all outflow ultimately is through the Snake River; however, throughout the reservoir area the river alternately gains and loses in several reaches before finally collecting all surface and ground-water discharge near the west end of the reservoir area. Some water that is diverted for irrigation cycles back into the aquifer system at least three times as it moves from the upper end to the lower end of the Southern Idaho ground-water reservoir.

In this region, largely because of the highly seasonal nature of the precipitation and snowmelt (p. 11), some runoff commonly escapes from most areas without apparent beneficial use. Management of the streamflow and aquifers conjunctively might provide the flexibility to salvage and store for later use some of this runoff. Such management might include intensive pumping for the deliberate drawdown of ground-water levels during periods of low stream flow to make space for additional recharge water available during periods of high runoff, provided this can be accomplished without serious reduction of streamflow during critical periods.

Conjunctive use of ground water and surface water probably represents the most widely available opportunity in the region for effectively managing the available water supplies. The benefits possible from this management approach are effectively blocked, however, by existing water-rights laws. In many areas efficient management will require flexibility to allow the source of water supplies to be shifted from stream to underground sources and back again in accordance with water availability. It also may require the readjudication of withdrawal periods and rates of withdrawal.

EFFICIENCIES IN CONVEYANCE AND USE

For some parts of the region, no matter how much emphasis is given to water supplies, the supply-demand equation cannot be balanced without sensible and effective conservation of the water. Fortunately, opportunities are available for conserving the ground water; some of these—reduction of water-loving plants, artificial recharge, and repair of leaky wells—were discussed previously.

A conservation opportunity of considerable promise is a relatively new method of irrigation—drip irrigation. Great savings of water are possible because much soil that is wetted during the conveyance and application of water in other irrigation methods remains dry during drip irrigation. Savings are also possible in fertilizer and some pesticides, which can be applied in the irrigation water, and in weed control. Other advantages include the virtual elimination of irrigation return flow with its degrading effect on water quality, avoidance of waterlogging resulting from excessive water application or irrigation return flow and, for some crops, a reduced need for level land. Constraints on widespread use of drip irrigation include capital investment required for pipelines and drip nozzles, major investments that already have been made in other irrigation systems, possibility of salt build-up in the soil, and some problems of clogging of the drip nozzles with particles such as weed seeds and with chemical precipitates.

Ground water not only is suitable for drip irrigation, it is a preferred supply. One major reason is that ground water usually can be delivered free of weed seeds, spores, algae, or other clogging agents. Sand or silt in water from some wells however, may be a problem, as in many surface-water supplies. Moreover, the smaller demand rate for irrigation water for this method favors the decentralizing of supply wells—that is, the use of several widely separated, smaller-yield wells with short, efficient supply lines instead of one large-yield well pumping into long supply lines or inefficient distribution ditches. The decentralizing of supply wells may have economic benefits even in areas where large-yield aquifers are available. In addition, the smaller water demand for the drip method makes irrigation with ground water much more attractive for areas where aquifers do not have the proven capability for the large yields normally required for irrigation by other methods.

Any other means of increasing efficiency in the use of the irrigation water or decreasing need for water application can also help stretch supplies of surface and ground water. Such improvements might include greater use of efficient sprinkler systems, or techniques of fertilizer application and soil treatment to reduce the need for excess water to flush the soil. Because of the huge amount of the total water withdrawal that is dedicated to irrigation (fig. 2), even small individual savings of irrigation water could be valuable. For example, a saving of only 18 percent in the average irrigation-water diversion or withdrawal in 1975 would have conserved water in an amount equivalent to all other withdrawals combined for that year (5 billion gallons per day).

MANAGEMENT USING PREDICTIVE MODELS

Research in the field of ground-water hydrology has, within the last two decades, developed a set of powerful tools for assisting water management—models of ground-water flow systems that allow prediction of conditions in the ground-water reservoir under different schemes of development. These models were made practical by recent advances in electronics and high-speed computers. Predictive models have been developed and used for several ground-water reservoirs in the region and are possible for other areas as well.

Ground-water models have been used to predict water-level changes likely to result from different rates and patterns of pumping withdrawal in the Columbia Plateau (about 10 models, some overlapping); the Southern Idaho (9 models); the Willamette Valley (1 model); and a few smaller ground-water reservoirs. Some models have been deliberately developed on the basis of preliminary or sketchy information in order to define sharply the data needed for a more reliable model to be used for management guidance. In addition, some models are being developed principally to predict the movement of contaminants in the ground water. A few of the ground-water models reflect the interrelationships of the streams and aquifer systems and, therefore, could guide management programs for conjunctive use of ground water and surface water (see section on "Conjunctive Use of Ground Water and Surface Water").

Constraints on the greater use of ground-water models include: The large investments in facilities, data handling, and time usually required for development of a reliable, effective model; lack of adequate data for modeling many ground-water reservoirs, a situation that often can be overcome only by collecting field data, which is expensive and time-consuming; a shortage of ground-water hydrologists with the skills, support, and facilities necessary for successful modeling of complex hydrologic systems; and the lack of assurance that, even with the best expectations, a reliable model can be developed that is suitable for the intended use. Despite these constraints, however, predictive ground-water models remain one of the more useful water-management tools available for problem areas that warrant, and are amenable to, modeling. Once calibrated and verified against actual conditions, such models can be used indefinitely, with appropriate modifications, for study of a large variety of water-management problems.

ENERGY-RELATED OPPORTUNITIES AND CONSTRAINTS

Events of the past few years have brought into sharp focus the dependency of the Pacific Northwest Region and the Nation on abundant energy. Accordingly, no contemporary analysis of resource-management opportunities and constraints would be complete without considering those related to energy.

Opportunities for energy-related uses of ground-water in the region appear at present to be few but may be substantial in the future. They include geothermal energy development; use of ground water in mining, processing and (or) movement of coal; small amounts of additional hydropower generation using ground water; and use of the ground water for disposal and (or) storage of heat. Ground-water problems associated with these possible uses include depletion of supplies and degradation of water quality.

GEOTHERMAL ENERGY

Naturally occurring hot ground water has been used in this region for several decades for irrigation and space heating, and is now being explored for wider applications, including generation of electrical power. Warm ground water is used for irrigation in many areas east of the Cascade Range, and thermal ground water also is used to heat buildings in the Boise and Sun Valley areas, Idaho.[1]

The term "geothermal resources" is commonly used to mean ground water or rocks hot enough to be of

[1]In the Klamath Falls area, Oregon, which is adjacent to but outside this region, the use of hot ground water for heating home, commercial, and institutional buildings is said to be the largest use of thermal ground water for space heating in the United States.

economic value—for example, to produce electrical power by releasing steam through drill holes for operation of turbine generators. About 120,000 acres of land in the region has been classed as being within KGRA's ("known geothermal resource areas"), that is, areas worthy of careful evaluation for geothermal potential (Godwin and others, 1971). These KGRA's are mainly in the vicinity of the volcanoes of the Cascade Range and in the areas of the High Cascades, High Desert, and Southern Idaho ground-water reservoirs. To date (1977), by far the most intensive drilling and testing has been done in the Raft River basin, Idaho (fig. 9). There, several dozen holes have been drilled for subsurface samples, heat-flow measurement, and production of hot water or steam. The deepest known geothermal test well in the region (6,543 feet) is in this basin.

None of the geothermal zones tapped has yielded water hotter than about 150°C, a temperature generally considered too low for efficient steam-power generation. However, experiments are planned at the Raft River basin site to investigate the practical applications of this low-temperature geothermal water for both electrical power generation and nonelectrical heat uses in industries related to agriculture and food processing. The experimental project is based on an integrated "energy park" concept, in which heat remaining after one use of the hot water would be used in other applications requiring successively lower temperatures. If this experimental project is successful, it may lead to more "energy parks" across southern Idaho and southeastern Oregon.

The hot water from the Raft River basin is similar to most other thermal waters of the region, in that it is saline enough to be a potential contaminant to other water resources. The dissolved-solids concentration in water from one core hole in that area was 6,650 mg/L in September 1974 (U.S. Geological Survey data).

HYDROPOWER GENERATION WITH GROUND WATER

One unusual, though small-scale, energy-related use of ground water in this region is for the generation of electrical power. In the Thousand Springs area of the Snake River canyon near Twin Falls, Idaho, the discharge from springs high on the canyon wall is so large that the water is collected in flumes and used to drive generators located on the canyon floor. The combination of copious spring flow and discharge of the water at a relatively high elevation is needed for this use of the ground water; the combination exists in few other areas of the region. However, opportunities probably exist in parts of the High Cascades ground-water reservoir, where very permeable young volcanic rocks underlie steep land and receive abundant recharge from precipitation. The abundant yield of the young volcanic rocks was confirmed in Linn County, Oregon, where a tunnel was driven to drain these rocks and produce extra water for hydropower generation (R. B. Sanderson, U.S. Geol. Survey, written communication).

GROUND WATER AND COAL

Coal is the only fossil fuel known to occur in commercial quantities in the Pacific Northwest Region. Most of the coal is in and near the area of the Puget Sound ground-water reservoir, and in the eastern foothills of the Cascade Range. The estimated reserves in Washington are sizable—more than 6 billion (short) tons, but the reserves consist largely of subbituminous coal and lignite (about 4.3 billion tons; Livingston, 1974, p. 41). In addition to the relatively low ranking and heat content of most of the coal, the coal beds have been contorted by folding and faulting so that they commonly are steeply dipping, discontinuous, or sheared. In only a few areas are dips of the beds gentle enough to permit strip mining. Despite these problems, Washington has had some coal production almost continuously since the late 1800's, the largest being a strip-mining operation near Centralia, Wash. (south of the Puget Sound ground-water reservoir); this operation supplies as much as 2.6 million tons a year to a nearby steam-electric generating plant (Livingston, 1974, p. 41).

Washington's coal has two important attributes that partly offset the aforementioned problems. One is that it is "low-sulfur" coal and, therefore, it offers some economic advantages in meeting environmental-protection requirements during mining and use. The other is that most of the coal occurs in reasonably close proximity to abundant water resources. This affords the possibility of using water for some forms of remote mining of the deep coal beds (hydraulic fracturing or flushing the broken coal to the surface), for conveying the coal in slurry pipelines, or for in-place gasification of the coal.

At a few places near the coal beds, ground water could be produced at rates that would be useful in such processes, but the main impact of future coal development on ground water is likely to be a degradation of water quality. Water-quality impacts of coal-mine drainage and possible increased production of coal in Washington are being assessed by the U.S. Geological Survey (Packard and Haushild, 1977).

SUBSURFACE STORAGE OF HEAT

Water has a very high specific heat, meaning that a comparatively large amount of heat can be added to, or taken from, water for a given change in the water's temperature. Also, slowly moving ground water and the rocks that enclose it conduct heat very slowly. These conditions make ground water advantageous for the storage of heat for later recovery. Similarly, the ground-water can be a sink for waste heat, although the cooling or assimilation rates using ground water normally cannot equal the rates possible with disposal of heat to streams or the atmosphere. Although there has been some use in the region of ground water for heat storage and disposal, much greater opportunities exist for utilizing the subsurface for the deliberate storage of heat.

Ground water has been used for disposal and storage of heat mainly in the Puget Sound and Willamette Valley ground-water reservoir areas, mostly in the Portland, Oreg. area (Price and others, 1965, p. 20–33). Although problems of clogging of the aquifers have been a constraint to the continued or more widespread use of this type of subsurface storage and disposal, these problems can be largely overcome by improved methods such as closed-loop transfer of the water, selection of permeable aquifers, and use of the best well-construction methods for injection wells. As energy costs rise, reverse-cycle heat-pump systems, using ground water as the heat reservoir, are likely to become more popular for homes and other buildings.

In addition to the saturated rocks available to serve as a heat reservoir, large bodies of permeable but unsaturated rocks are available, especially in arid parts of the region, that might serve for storage of local sources of heat—for example, heat from solar-collection systems or waste heat from power-generation facilities.

SUMMARY OF NEEDS FOR ADDITIONAL INFORMATION

The need for additional information is a recurring theme in this appraisal. State officials who were contacted, contributing hydrologists, technical reviewers, as well as this writer, generally agree that improved management of the ground-water resources in the Pacific Northwest Region is seriously hampered by information inadequacies. The scarcity of unappropriated surface water and accelerating uses of ground water are increasing the water-related problems and intensifying the need for ground-water management. Some difficult and far-reaching decisions are being made or must be made about the region's ground-water resources within the next decade. Without sound technical information, those decisions must be based largely on supposition and conjecture.

Opinions differ as to which kinds of information are most needed and in what degree of detail. Judgments of this nature will be important because the total amount and variety of ground-water-related information that could be beneficially used within the next decade seem far beyond the present capabilities of hydrologists and others to supply. Efficiencies in the use of the limited technical manpower can be fostered by anticipating problems and maintaining an orderly program of investigations and research to provide information before water problems reach crisis proportions.

The water managers of the region need ground-water information for the following purposes:

1. To assess the resource—a recurring need that, for some parts of the region, has not been met even the first time;
2. to detect changes with time;
3. to make sound management responses to current problems;
4. to identify developing or future problems, and to formulate strategies for forestalling, circumventing, or mitigating the problems;
5. to gain public understanding of and support for the needs to manage the ground water;
6. to combine scientific knowledge with economic, social, and political considerations as a basis for formulating water-resources policies.

The kinds of ground-water data, investigations, and research that are needed by the water managers and others in the coming decade range widely, in accordance with the varied settings and problems of the region. Discussion of the full range of information needs is beyond the scope of this summary section, but the following general statements seem pertinent:

1. Ground-water-quality data, evaluations, and monitoring will be needed increasingly.
2. More complete and reliable information on ground-water withdrawals and resultant water-level declines is needed for all the major and many smaller ground-water reservoirs.
3. Although reconnaissance-type data will continue to be adequate for some purposes, more quantitative, detailed information will be required, especially in problem areas, areas destined for conjunctive use of surface and ground water, and areas considered for disposal of wastes.
4. More perspective will be needed of the total ground-water reservoir or basin—the geologic framework and controls on the ground water; places and amounts of recharge and discharge; ground-water flow patterns (including deep parts of the reservoirs); hydraulic characteristics of the rock mate-

rials; and quality of the ground water throughout.

5. The more detailed, extensive, and quantitative information will be more difficult and expensive to obtain, in general. Some information about deeper parts of the ground-water reservoirs can be obtained only by the drilling and testing of expensive, deep wells. Though not substitutes for the deep-well information, geologic mapping and geophysical surveys likely will be used increasingly to extend the information returns from deep test-observation wells.
6. As the ground-water management problems increase in complexity, they will require reliable interpretations of greater sophistication and incisiveness. Mathematical models of ground-water flow systems will remain as powerful interpretive tools and will maintain a high level of demand for quantitative basic data.
7. Presentation and dissemination of the ground-water information in a clear and understandable form will continue to be nearly as important, for some purposes, as the information itself.

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